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Full-Scale Water Mist Design Parameters Testing

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16. Abstract (MAXIMUM 200 WORDS)

The overall objective of this evaluation was to further develop an understanding of the capabilities and limitations of water mist systems as applied to machinery space applications. The primary objective of this investigation was to evaluate the applicability of a local application test method being considered by the International Maritime Organization (IMO). An evaluation of the effects of mist spray obstructions on extinguishment capabilities was performed. The effects of compartment parameters (size and vent area), mist system parameters (system flow rate), and fire parameters (heat release rate, fire type, location, and degree of obstruction) were evaluated to aid in validating a scalability model. This model can be used to scale test results to other sized compartments.

Local application water mist systems are capable of extinguishing spray and pan fires if they produce sufficient mist concentrations uniformly around the protected object. They do have limited capabilities against obstructed fires. The size of the obstruction and separation distance between the obstruction and the fire were identified as primary variables. A steady state model was validated that predicts compartment temperatures, oxygen concentrations, and critical fire sizes.

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EXECUTIVE SUMMARY

An investigation was conducted to further develop an understanding of the capabilities and limitations of water mist systems as they apply to machinery space applications. The primary objective of the investigation was to evaluate the applicability of a local application test method currently being considered by the International Maritime Organization (IMO). In addition, the effects of compartment parameters (size and vent area), mist system parameters (mist system flow rate), and fire parameters (heat release rate, fire type, location, and degree of obstruction) were also evaluated.

The U.S. Coast Guard's Research and Development Center has been actively involved in the research effort to identify alternative fire suppression methods and/or agents for Halon 1301 total flooding systems. The research, to date, has focused on both the gaseous halon alternatives and water mist technologies. The International Maritime Organization currently allows the protection of machinery spaces with total flooding water mist systems. The IMO is currently considering the use of water mist as a local application system to be used in conjunction with a total compartment protection system. These recent developments are of interest to the Coast Guard for two reasons: (1) to provide protection of the machinery spaces for their new classes of cutters, and (2) to provide data for U.S. regulatory acceptance of water mist technologies.

In September 1996, the Fire Protection Sub-Committee of the IMO Maritime Safety Committee discussed the use of water mist as a local application system to be used in conjunction with a total compartment (flooding) protection system. The use of water mist as a local application system is relatively untested outside of a limited number of tests conducted by the Japanese and the applications described in NFPA 15 [7]. The test series described in this report was initiated to address many of these unresolved issues associated with the use of water mist, as both a total flooding system and a local application system in machinery space applications.

Over one hundred and fifty full-scale fire suppression tests were conducted during this investigation. The tests were conducted in a simulated machinery space aboard the test vessel, STATE OF MAINE, at the U.S. Coast Guard Fire and Safety Test Detachment located at Little Sand Island in Mobile, AL. The compartment was constructed to meet the dimensional (500 m^3) requirements of the IMO test protocols for evaluating total flooding systems. Four generic water mist systems produced using off-the-shelf industrial spray nozzles and one UL listed NFPA-15 water spray system were included in this evaluation. The information collected during this test series supports the following conclusions:

- Local application water mist systems are capable of extinguishing a variety of heptane or diesel spray and pool fires if the nozzles are installed above the hazard and the system is designed to produce a sufficient mist concentration uniformly around the object being protected. Local application water mist systems have limited capabilities against obstructed fires, requiring additional measures for obstructed areas. When a system was not capable of extinguishing the fire, the thermal conditions produced by the fire were significantly reduced (30-70% reduction). The results of these tests also aided in the further development of a test protocol for evaluating local application water mist systems.
- The ability of total flooding water mist systems to extinguish small fires is related to the degree of obstruction of the fire. The size of an obstruction and the distance between an obstruction and the fire were identified as the primary variables associated with the effectiveness in the extinguishment of these fires. As the size of the obstruction was increased or the distance between the fire and the obstruction was decreased, the extinguishment times increased.
- A steady state model developed during the initial phase of this investigation was validated for a range of fire sizes, ventilation conditions, and water mist flow rates. The model was able to accurately predict the steady state compartment temperatures, oxygen concentrations, and critical fire size for the tests conducted during this investigation. The model has served as the foundation for the development of a transient model.

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1.0 INTRODUCTION

The U.S. Coast Guard's Research and Development Center has been actively involved in the research effort to identify alternative fire suppression methods and/or agents for Halon 1301 total flooding systems. The research, to date, has focused on both the gaseous halon alternatives and water mist. The International Maritime Organization (IMO) currently allows the protection of machinery spaces with total flooding water mist systems. The IMO is currently considering the use of water mist as a local application system to be used in conjunction with a total compartment protection system. These recent developments are of interest to the Coast Guard for two reasons: (1) to provide protection of the machinery spaces for their new class of cutters (G-S), and (2) to provide data for U.S. regulatory acceptance of water mist technologies (G-M). Consequently, this project has two Coast Guard Headquarters sponsors, the Marine Safety and Environmental Protection Section (G-M) and the Systems Section (G-S).

In December 1994, the IMO Maritime Safety Committee approved guidelines for alternative arrangements for halon fire extinguishing systems (MSC Circular 668) [1]. Annex B of the guidelines provides an interim test method for evaluating equivalent water-based fire extinguishing systems for Category A machinery spaces and cargo pump rooms (Appendix A). Since the development of the guidelines, numerous research programs [2,3,4,5] have demonstrated that, if properly designed and tested, water mist fire suppression systems can afford effective protection of Category A machinery spaces. These tests have also identified areas in the standard that need to be addressed. Two such areas are the extrapolation of the test results obtained in the IMO enclosure to larger machinery spaces, and to develop an understanding of how fire obstructions affect the extinguishment capabilities of the various commercially available systems.

In September 1996, The Fire Protection Sub-Committee of the IMO Maritime Safety Committee discussed the use of water mist as a local application system to be used in conjunction with a total compartment (flooding) protection system. The proposed Japanese test method [6] is found in Appendix A. The use of water mist as a local application system is relatively untested outside the tests conducted by the Japanese and the applications described in NFPA 15 [7]. This experimental program was initiated to address many of these unresolved issues associated with the use of water mist, as both a total flooding system and a local application system in machinery space applications.

2.0 OBJECTIVES

The overall objective of this evaluation was to further develop an understanding of the capabilities and limitations of water mist systems as applied to machinery space applications. More specific objectives are listed as follows:

- Identify the capabilities and limitations of the use of water mist as a local application type system, and to develop a foundation for a local application test protocol;

- Further develop an understanding of how fire obstructions affect the capabilities of water mist systems;

- Further develop an understanding of how to extrapolate the results of the IMO test protocol to larger, more realistic machinery spaces and to machinery spaces with different ventilation openings; and

- Characterize the effect that water mist has on the compartment environment (i.e., visibility and temperature).

3.0 TECHNICAL APPROACH

3.1 Local Application

The objective of the local application evaluation was to identify the capabilities and limitations of the use of water mist as a local application type system and to develop a foundation for a local application test protocol. The approach consisted of identifying the capabilities of four representative water mist systems as a function of nozzle spacing and the distance between the nozzles and the object being protected.

The four water mist systems evaluated were produced using off the-shelf industrial spray nozzles. The capabilities of these four systems were compared to an Underwriters Laboratories (UL) listed National Fire Protection Association (NFPA-15) water spray system. The four generic water mist systems produced spray characteristics representing the extremes of the currently available water mist hardware. The systems include a wide and narrow angle low pressure Class 3 spray and a wide and narrow angle high pressure Class 1–2 spray as defined in NFPA 750 [8]. This approach allowed the data collected during this evaluation to be applied across the range of current water mist technologies as appropriate.

The local application water mist systems were evaluated on both their ability to control and extinguish the test fires. The extinguishment evaluation was conducted against a series of heptane and diesel spray and pan fires. The fires were located on either the top or the side of the IMO diesel engine mockup. The control evaluation was based on the systems ability to cool the hot gases in the plume and localize any thermal damage. The cooling evaluation was conducted against the fires not extinguished by the water mist system. These were primarily the spray fires located on the side of the mockup. During all of the local application tests, the compartment was well ventilated to prevent the fires from reducing the oxygen concentration in the space. Previous tests have shown increased extinguishment capabilities of water mist systems in compartments with reduced oxygen concentrations. In larger machinery spaces, a reduction in oxygen is unlikely.

The nozzles were evaluated in both a vertical and horizontal orientation. Some shipboard installation may consist of nozzles installed on all sides of the hazard. The approach of evaluating these systems separately represented a worst case condition with only the mist from the nozzles aimed perpendicular to the protected surface reaching the fire. Any mist reaching the fire from nozzles aimed at other surfaces should only increase the capabilities of the system. This approach also provided a high degree of confidence in broader use applications. The vertical configuration consisted of nozzles aiming downward on top of or along side of the diesel engine mockup with the fire located under the nozzles. The horizontal configuration consisted of nozzles aiming horizontally toward the shielded side of the engine mockup with the fire located under the one meter obstruction plate. It was originally intended to identify the maximum distance away from the mockup the system could be installed and still extinguish the test fires for a range of nozzle spacings (1.0-3.0 m). Due to the limited capabilities of the generic local application systems as presented in the results (9.1.1) section, only a 2.0 m distance was evaluated. One and two meter nozzle spacings were evaluated. The UL listed water spray system was evaluated with two nozzle spacings (1.0 m and 2.0 m) and one distance away from the mockup (2.0 m per the listing).

It was originally intended to evaluate the effect of obstructions on the capabilities of the local application water mist systems. This evaluation was eliminated due to reduced performance in areas of low mist concentrations (see Extinguishment Analysis 9.1.1).

3.2 Fire Obstruction Evaluation

The objective of the fire obstruction evaluation was to determine how obstructions affect the fire extinguishment capabilities of total flooding water mist systems. The approach consisted of conducting a series of fire extinguishment tests with varying degrees of fire obstructions to develop a relation between fire obstruction and extinguishment time. Obstructions consisted of two different size steel plates positioned at various distances above the fire. The outcome of this evaluation has the potential of identifying areas in the space requiring addition protection other than the overhead nozzle grid as required by IMO.

Two generic total flooding water mist systems, produced using off-the shelf industrial spray nozzles were included in this evaluation. The spray characteristics (i.e., droplet sizes) of these two systems covered the range produced by the currently available water mist hardware (a low pressure Class 3 spray and a high pressure Class 1–2 spray, as identified by NFPA 750 [8]). The mist application rates (flow rate per unit floor area) were also representative of the currently available hardware. The nozzles were installed at the overhead with a uniform nozzle spacing as required by IMO. This system design (1.5 m nozzle spacing) was similar to the one tested previously [3].

The evaluation was conducted against small diesel pan fires (5 kW — tell-tale fires) with a selected number of tests repeated against a larger fire (100 kW diesel pan fire). It was originally intended to use heptane as the test fuel, but the small heptane fires could not be extinguished by the total flooding water mist systems evaluated during this test series.

The approach was to develop a relation between various obstruction sizes, the distance between the obstruction and the water mist nozzles, and the distance between the fire and the obstruction. These two distances ranged from one to three meters. The obstruction plates measured 1.0 m x 1.0 m and 0.5 m x 1.0 m. The evaluation was conducted in a worst case location (i.e., between water mist nozzles). The fire obstruction evaluation was conducted in a compartment with limited ventilation to allow the mist concentration to increase with time. Although the compartment was closed, the oxygen concentration in the compartment remained at ambient due to the small size of the test fires.

3.3 Scaling Evaluation

The objective of the scaling evaluation was to gather information pertaining to the extrapolation of the test results collected in the IMO test compartment to larger, more realistic machinery spaces, and/or to machinery spaces with different ventilation conditions. The approach consisted of conducting a series of fire extinguishing tests controlling the oxygen concentration in the compartment through changes in ventilation conditions. The information collected during these tests aided in the further development of an extinguishment model developed during the initial phase of this investigation [3]. The model was developed to provide scaling information applicable to designing and approving systems for machinery spaces with volumes greater than 500 m^3 and for machinery spaces with different ventilation conditions.

The two generic total flooding systems, one high pressure and one low pressure, were used during these tests. The systems were evaluated against a series of fires conducted on the side (obstructed) of the IMO diesel engine mockup. The fires were produced using heptane as the fuel and consisted of various size spray fires (0.3 - 1.0 MW), and one pan fire (1.0 MW). These fire tests were conducted in a compartment with a range of ventilation conditions (1.1, 2.0, and 4.0 m^2 openings). In addition, the smallest fire that could be extinguished for each of the three vent openings was also identified for both systems.

The effect that mist application rate has on fire extinguishment time was also evaluated. The previous tests were repeated using the generic small droplet system (high pressure Class 1-2 spray) with application rates that ranged from 1.2 - 3.3 Lpm/m^2. The size/capacity of the water mist nozzles and the operating pressures were varied to produce these application rates. Consequently, the nozzle spacing remained constant during this evaluation.

3.4 Compartment Environment Evaluation

The effect that water mist had on the compartment environment was measured during the local application evaluation. The approach was to provide additional instrumentation to measure how the presence of mist impacts the visibility, thermal conditions in the space, and the products of combustion (i.e., carbon monoxide). The previous phase of this investigation provided information on the conditions in the compartment during extinguishment of a fire using a total flooding water mist system.

During the local application evaluation, the conditions in the space (temperatures, optical densities, and gas concentration) were measured using the same compartment instrumentation scheme. The measurements recorded during the local application tests were compared to a series of free burn tests to evaluate the impact the mist had on the compartment environment.

4.0 TEST COMPARTMENT

The tests were conducted in a simulated machinery space aboard the test vessel, STATE OF MAINE, at the U.S. Coast Guard Fire and Safety Test Detachment located at Little Sand Island in Mobile, AL. The simulated machinery space was located on the fourth deck of the Number 6 cargo hold. The compartment was constructed to meet the dimensional requirements of the IMO test protocol. The compartment volume was approximately 500 m^3 with nominal dimensions of 10 m x 10 m x 5 m as shown in Figure 1. The IMO diesel engine mockup described in the test protocol was located on the fourth deck in the center of the compartment as shown in Figure 2. The compartment contained three large vent openings (two 2 m^2 vent openings located on the fourth deck forward in the compartment and a 6 m^2 vertical stack located aft in the overhead of the compartment) and four standard ship board doors (two located on the fourth deck and two located on the third deck aft forward in the compartment). During the local application evaluation, a 170 m^3/min blower was used to provide additional air for combustion. This provided fresh air at a rate of 20 air changes per hour.

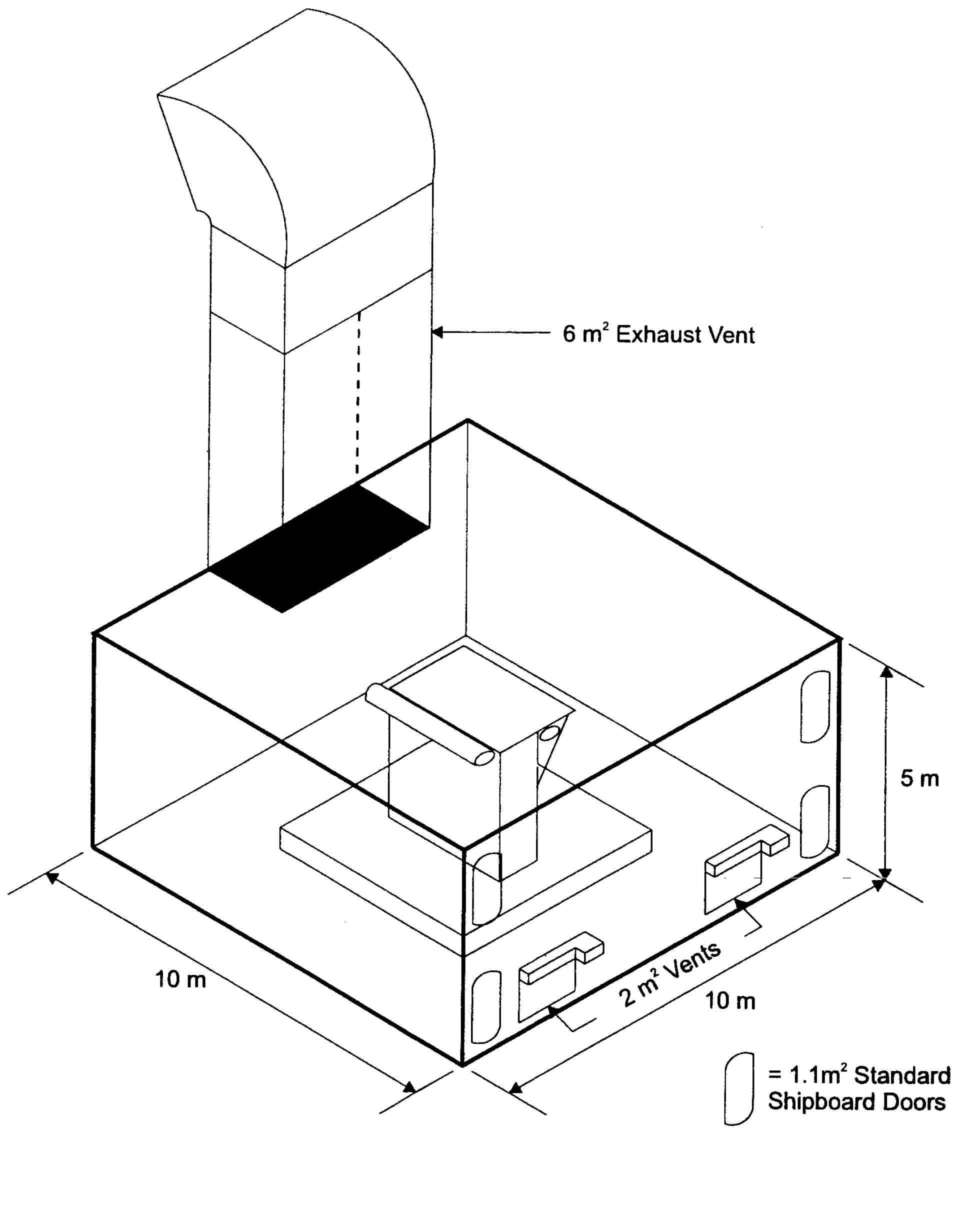
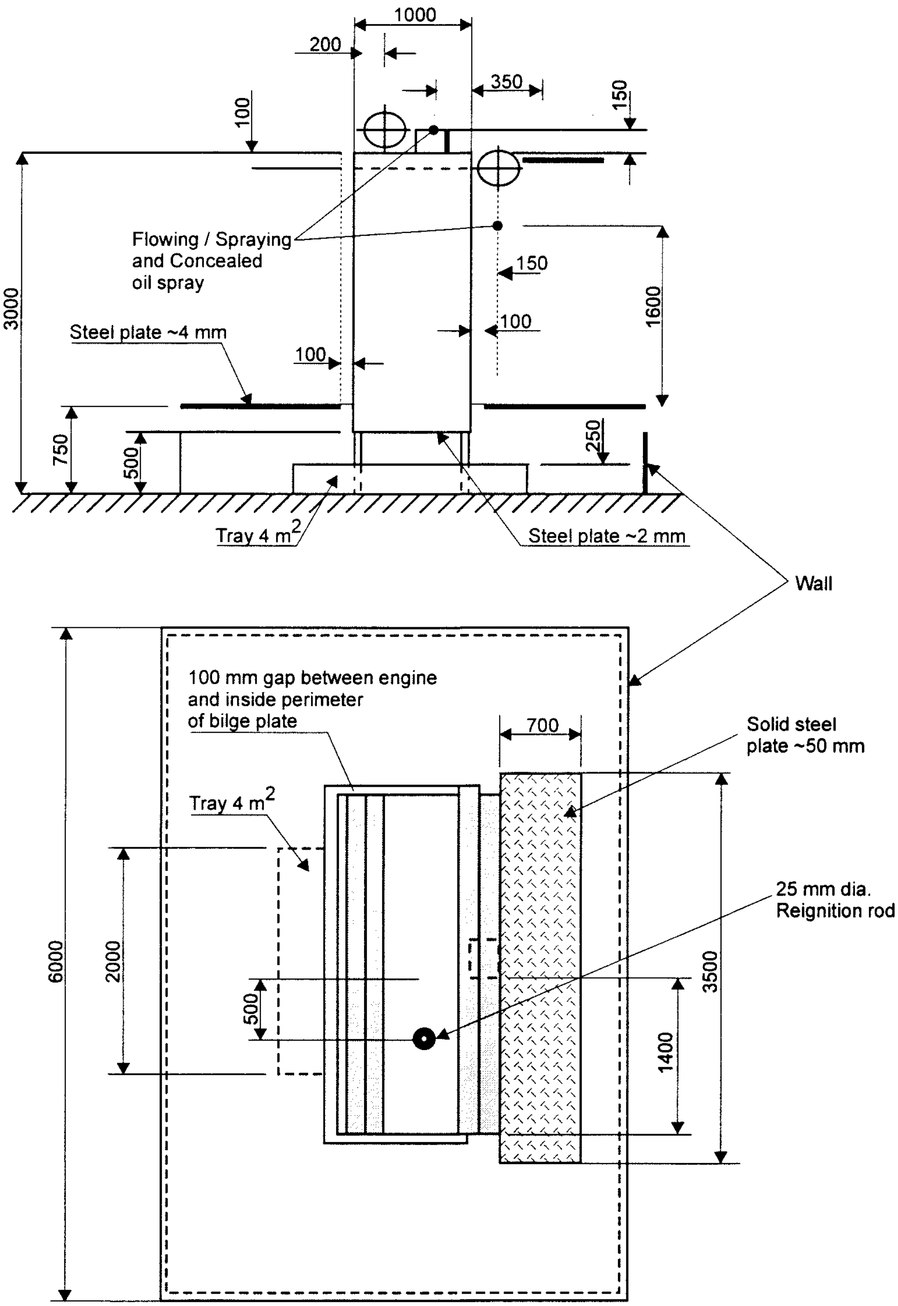


Figure 1. Machinery space configuration



(All measurements are in mm, unless otherwise noted.)

Figure 2. Diesel engine mock-up

The following ventilation conditions were used for the various phases of this experimental program:

- Local Application Evaluation - The 6 m^2 vertical stack damper was open and the supply air blower was activated. All other vents in the compartment were closed.

- Fire Obstruction Evaluation - The starboard 2 m^2 IMO vent located forward in the compartment was open. All other vents in the compartment were closed during the tests.

- Scaling Evaluation - The two 2 m^2 vents located on the fourth deck forward in the compartment were set to the value identified in the test matrix. All other vents in the compartment were closed during the tests.

5.0 WATER MIST SYSTEM(S)

5.1 Pipe Network(s)

Two types of water mist systems were included in this evaluation: a total flooding system and a local application system. These two systems were constructed as follows.

5.1.1 Total Flooding System

The total flooding water mist system was similar to the one tested previously [3]. The system consisted of an overhead nozzle grid containing 36 nozzles uniformly spaced with a nominal 1.5 m nozzle spacing (Figure 3). The system was constructed of 2.5 cm (1 in.) stainless steel tubing with a 2.1 mm wall thickness and connected together with stainless steel compression fittings. Stainless steel tubing and fittings were required to prevent rust and corrosion from developing inside the pipe network. The working pressure of the system was 200 bar.

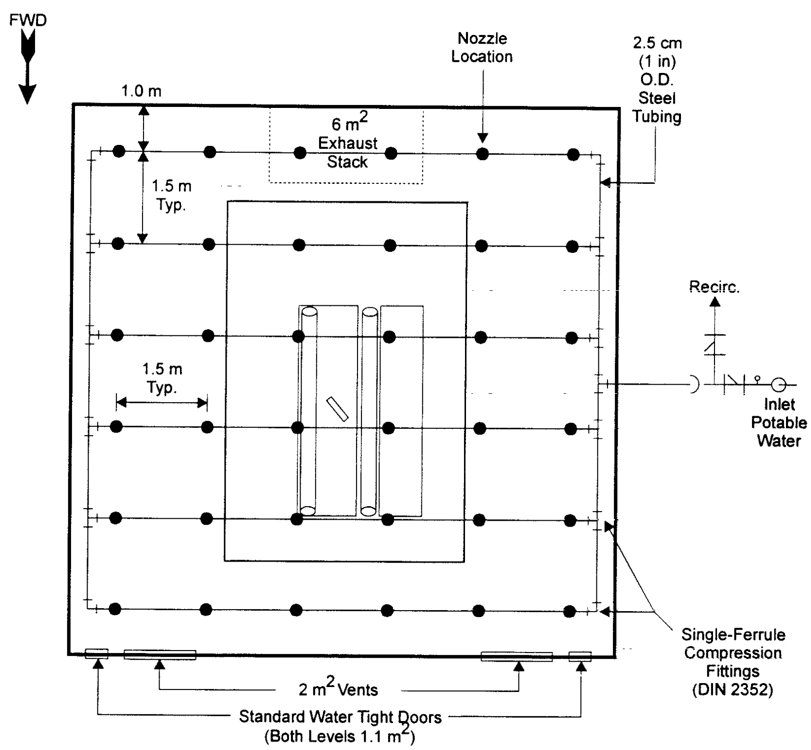


Figure 3. Total flooding water mist system

5.1.2 Local Application System

The local application water mist system was designed to protect the IMO diesel engine mockup located in the center of the space. A nine nozzle grid (3 by 3) was installed above and along one side of the IMO diesel engine mockup. The nozzles in the grid were installed with a nominal 1.0 m nozzle spacing (Figure 4). The system was designed to allow the positioning of the nozzle grid at distances from one to three meters from the mockup. The system was constructed of 2.5 cm (1.0 in.) stainless steel tubing and fittings as above.

5.2 Pumping System

A high pressure pumping system was used to provide water to both the total flooding and local application systems. The pump system had a minimum capacity of 380 Lpm at 70 bar. The pump system was equipped with a pressure regulating unloader valve to allow flexibility in setting the pressure of the system for the higher operating pressures and a manually controlled bypass line for setting the pressure in the lower pressure ranges. The net result was a pump system that could provide the required flow rate (380 Lpm) over the range of pressures from 5-70 bar.

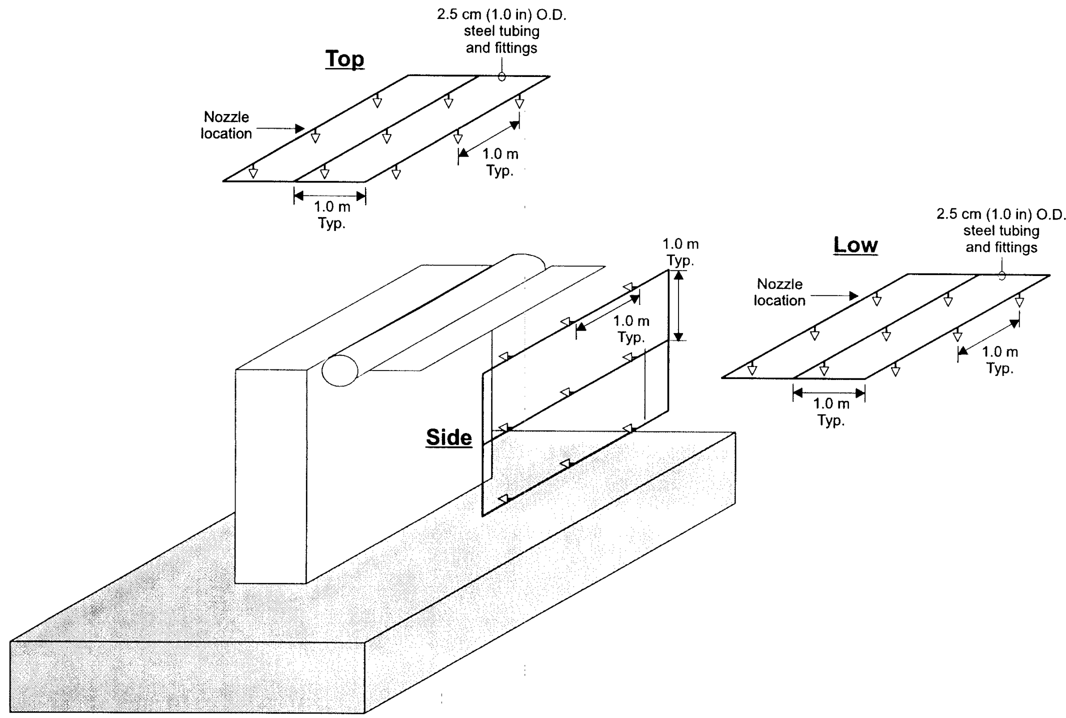


Figure 4. Local application water mist systems

5.3 Water Mist Nozzles

During this evaluation, the candidate water mist systems were produced using off-the shelf industrial spray nozzles manufactured by either Bete Fog Nozzle, Inc. or Spraying Systems, Co. The nozzles were selected to produce the desired spray and flow characteristics for the specific test. A list of the candidate nozzles is shown in Table 1. The nozzles listed in this table provided the wide range of droplet sizes and flow rates required to represent the currently available water mist system hardware. The spray characteristics of the nozzles used during these tests were characterized (i.e., flow rate (k-factor), droplet size, spray pattern, and spray momentum) in the laboratory at Hughes Associates, Inc. (HAI) prior to the full-scale investigation. These spray characteristics are found in Appendix B.

Table 1. Candidate Systems/Nozzles

Nozzle Designation	Operating Pressure (bar)	Spray Classification	k-factor (Lpm-bar$^{2/2}$)
UL/NFPA-15	7	Sprinkler	16.85
Generic 1 (G-1)	5	Class 2-3 mist	4.3
Generic 2 (G-2)	70	Class 1–2	1.0
Generic 3 (G-3)	10	Class 2-3	3.2
Generic 4 (G-4)	70	Class 1–2	0.9
Generic 5 (G-5)	35	Class 1-2	0.43
Generic 6 (G-6)	70	Class 1-2	1.9

6.0 FIRE SCENARIOS

Various fire types and sizes were included in this evaluation. Fires consisted of either pan or spray fires produced using heptane or diesel fuel. The locations of these fires are shown in Figure 5.

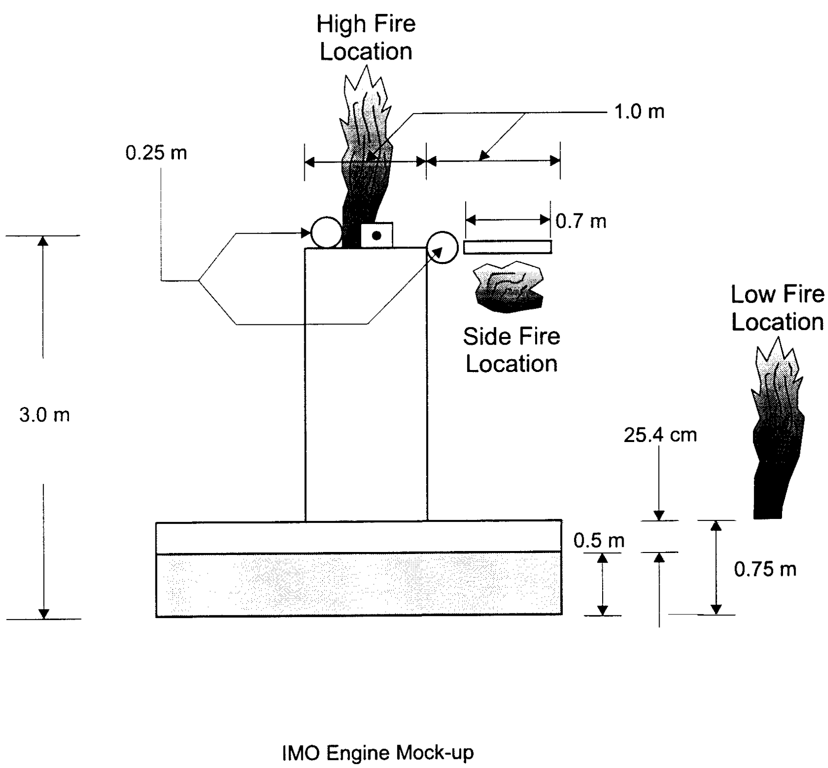


Figure 5. Fire locations

The primary fire sizes ranged from 0.3 to 6.0 MW for both the spray and pan fires. The spray fires were produced using the pressurized fuel system shown in Figure 6. The fuel sprays were produced used P series nozzles manufactured by Bete Fog Nozzle Inc. The following nozzles were included in this evaluation (P20, P28, P40, P48, P54, P80, and P120). The fires produced by these nozzles and pan sizes are shown in Table 2. The actual heat release rates of these fires were estimated based on the fuel nozzle pressure measured during these tests.

Table 2. Spray Fire Sizes

Nozzle Model	Pressure (bar)	Heat Release Rates	
		Heptane (MW)	Diesel (MW)
P20	3.5	0.143	0.166
P28	3.5	0.287	0.332
P40	3.5	0.592	0.686
P48	3.5	0.85	1.000
P54	3.5	1.127	1.300
P80	3.5	2.31	2.674
P120	3.5	5.2	6.0

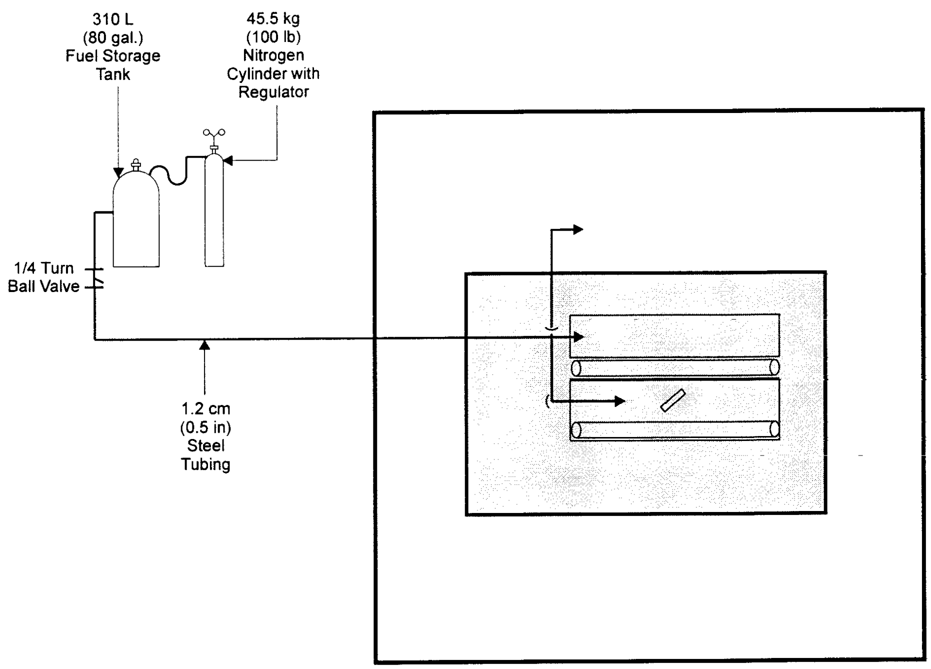


Figure 6. Pressurized fuel system

The fuel pans were constructed of 3.2 mm steel plate with welded seams. In all pan fire tests, the pans contained a 2.5 cm water substrate and 5.0 cm of fuel. During the tests conducted with the diesel fuel, 114 mL of heptane was used as an ignition aid. The following pan sizes were included in this evaluation (square pans X 0.3, 0.4, 0.55, and 0.75 m edge length). The theoretical heat release rates of these fires were calculated [9] and are shown in Table 3. The actual heat release rates of these fires were also estimated based on the fuel regression rate as determined by a pressure transducer installed in the bottom of each pan.

Table 3. Pan Fire Sizes

Size (m^2)	**Length (L)**	**Heat Release Rates**	
		Heptane (MW)	**Diesel (MW)**
0.091	0.301	0.128	0.088
0.166	0.401	0.297	0.201
0.312	0.558	0.702	0.459
0.554	0.744	1.505	0.951

During the fire obstruction evaluation, the locations of both the fires and fire obstructions were varied between tests. The fire obstruction apparatus is shown in Figure 7. Obstruction sizes and locations were varied as required to evaluate the system’s capabilities against obstructed fires. The obstructions were produced using 3 mm (1/8 in.) sheet steel. The majority of the obstructed fire tests were conducted against tell-tale fires. Tell-tale fires are small pan fires measuring 5.0 cm in diameter and approximately 10.0 cm tall. These fires were produced using either heptane or diesel fuel.

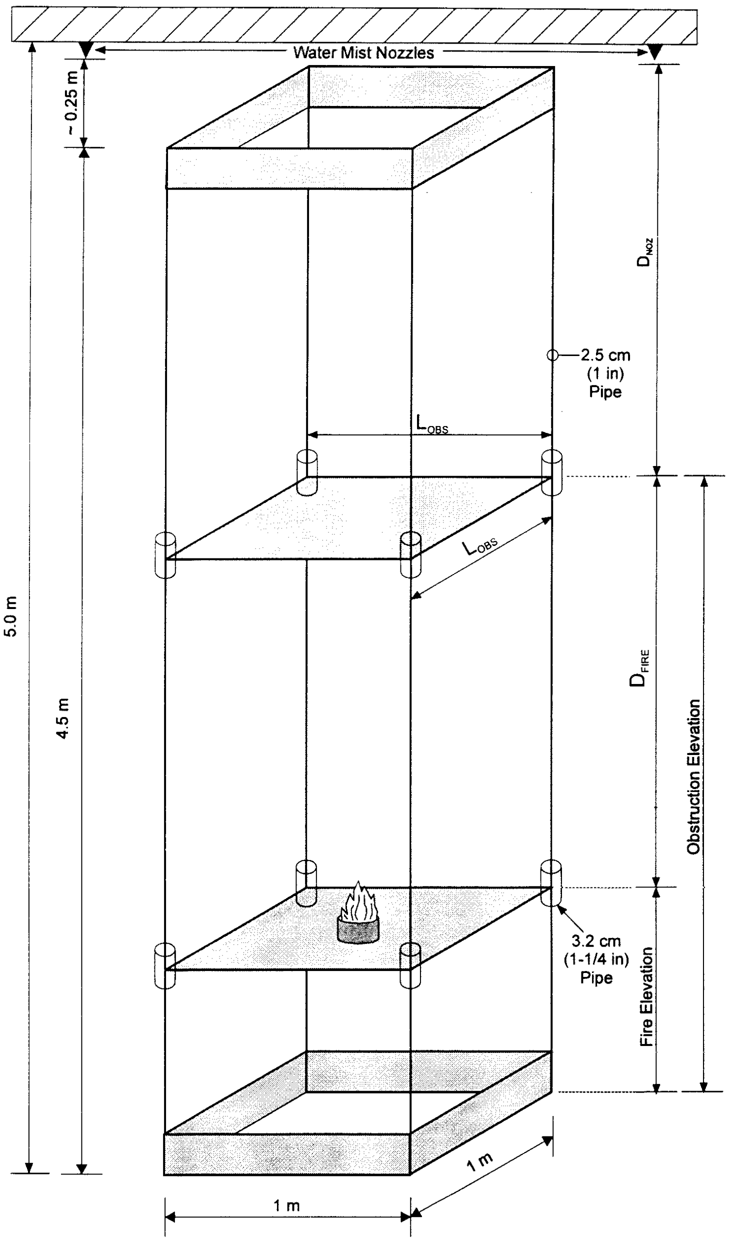


Figure 7. Fire obstruction apparatus

7.0 INSTRUMENTATION

7.1 Machinery Space Instrumentation

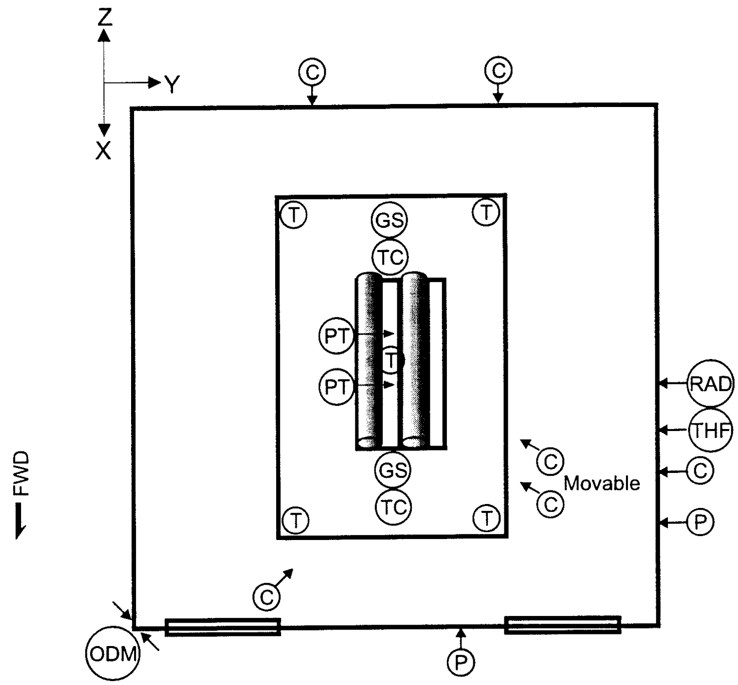
The machinery space was instrumented to measure both the thermal conditions in the space as well as the range of typical fire gas concentrations. Instruments were installed to measure air temperatures, fire/flame temperature (to note extinguishment time), radiant and total heat flux, compartment pressure, optical density, and O_2, CO_2 and CO gas concentrations as shown in Figure 8. Measurements were taken at a rate of one scan every six seconds. A complete list of instruments and instrument location is found in Appendix C. A more detailed description of the instrumentation scheme is listed as follows.

7.1.1 Temperature Measurements

Two thermocouple trees were installed in the compartment. Each tree consisted of eight type K inconel sheathed (3.25 mm dia.) thermocouples positioned the following heights above the lower deck (1.0, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 4.9 m). Hot gas temperatures were measured just below (5.0 cm) the overhead at five locations around the IMO diesel engine mockup. One thermocouple was installed above each corner of the bilge area and one directly above the center of the mockup. Two Swedish designed plate-type thermometers were also used to measure the hot gas temperature at the ceiling [10]. These two devices were installed in the overhead 1.0 m on both sides of the center of the space.

7.1.2 Gas Concentration Measurements

Carbon monoxide, carbon dioxide, and oxygen concentrations were sampled at six locations. These concentration were measured at the center line of the space both forward and aft of the engine mockup. Measurements were made 1.0, 2.5, and 4.0 m above the lower deck. The



GS	Gas Sampling CO, CO_2, O_2	(1.0, 2.5, 4.0 m)
TC	Thermocouple Trees	(1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0 m)
RAD	Radiometers	(2.0, 4.0 m)
THF	Calorimeters	(2.0, 4.0 m)
P	Pressure Measurements	(1.5 m)
C	Video Cameras	(1.5 m)
T	Hot Gas Thermocouples	(4.95 m)
ODM	Optical Density Meters	(1.0,2.5,4.0 m)
PT	Plate Thermocouples	(4.9 m)

Figure 8. Instrumentation

oxygen concentration was also measured in the exhaust stack and at the base of each fire conducted during this evaluation.

Carbon monoxide and carbon dioxide were measured using Lira series 300 gas analyzers. Oxygen was measured using Beckmen/Rosemont series 700 gas analyzers. The instruments were set to the following ranges CO - 0-5%, CO_2 - 0-25%, and O_2 - 0-25%. The analyzers had a transient/response time of approximately fifteen seconds.

7.1.3 Heat Flux Measurements

Both radiant and total heat flux measurements were recorded at four locations in the compartment. These transducers were installed on the forward and port bulkheads 2.0 and 4.0 m above the lower deck. Schmidt Boelter transducers manufactured by Medtherm Co. and having a full-scale range of 0-50 kW/m^2 were used for this application. The radiometers were equipped with 150E sapphire windows.

7.1.4 Compartment Pressure Measurements

The compartment pressure was measured at two locations in the space (the forward and port bulkheads 1.5 m above the deck). Setra Model 280E pressure transducers with a range of $\pm$ 2.48 kPa were used for this application. These instruments have an accuracy of 0.01 percent full scale.

7.1.5 Optical Density Meters

Three laser optical density meters were installed to measure the obscuration across one corner of the compartment at three elevations. These measurements aided in estimating both the mist concentration and the visibility in the space. The meters were installed with a path length of 0.3 m at elevations of 1.0, 2.5, and 4.0 m above the lower deck.

7.2 Water Mist System Instrumentation

The water mist system was instrumented to provide system and nozzle operating pressures, and total water flow rate.

7.2.1 Pressure Measurements

System pressures were measured at two locations: at the pump discharge and at the most remote nozzle location. Setra Model 280E pressure transducers were used for this application. These transducers have a range of 0-100 bar with an accuracy of 0.01 percent full scale or 0.01 bar.

7.2.2 Water Flow Rate Measurements

The flow rate of the water mist system was measured using two (nominal 1-½ in.) paddle wheel type flow meters. The flow meters were installed just upstream of the pump inlet and in the bypass line. The flow meters have a range of 50-500 Lpm with an accuracy of 0.1 percent full-scale or 0.5 Lpm.

7.3 Fire Instrumentation

Each fire scenario contained specific instrumentation to determine extinguishment times and heat release rates of the fires. A more detailed description of these instruments is listed as follows.

7.3.1 Fire Temperature Measurements

Two thermocouples were located in the flame/plume of each fire to determine extinguishment times. Inconel sheathed type K thermocouples (3.25 mm dia.) were used for this application.

7.3.2 Heat Release Rate Measurements and Estimations

7.3.2.1 Spray Fires

The published k-factor and the measured nozzle pressure were used to calculate the fuel flow rates in each spray fire test. The energy release rates of the spray fires were then calculated using the fuel flow rate and heat combustion of the fuel (nominally 44 MJ/kg). This assumes that all of the fuel is consumed with a 100 percent combustion efficiency. The fuel nozzle pressure transducers had a range of 0-690 kPa and an accuracy of 0.01 percent full scale.

7.3.2.2 Pan Fires

The fuel regression rate, fuel surface area and the heat of combustion of the fuel (nominally 44 MJ/kg) were used to estimate the heat release rates of the pan fires. The fuel regression rate was measured using a pressure transducer installed in the bottom of each pan. These pressure transducers had a range of 0-1380 Pa and an accuracy of 0.01 percent full scale.

7.4 Video Equipment

Five video cameras were used during each test. Two video cameras, one standard and one infrared (IR), were movable and located inside the compartment. These two cameras were typically positioned side-by-side approximately 3.0 m from the fire at the same elevation of the fire. The other three cameras were located 1.5 m above the deck, outside the compartment primarily viewing the area around the IMO diesel engine mockup. A microphone was installed in the center of the space to provide the audio for the five video cameras.

8.0 TEST OVERVIEW

8.1 Test Sequence

Over 200 tests were planned for this investigation. Many of these tests were eliminated from the investigation due to the results observed during other tests. The test logic and a matrix of the planned tests are described in the following sections. The 158 actual tests conducted are listed in Appendix D.

8.1.1 Local Application Tests

Approximately one hundred local application water mist tests were planned during this investigation. The tests were intended to evaluate the capabilities and limitation of two generic water mist systems and one UL-listed/NFPA-15 water spray system. Due to the results of the spray characterization conducted at the HAI laboratory prior to these tests, four generic water mist systems were included in this evaluation. These four systems were evaluated with either a one or two meter nozzle spacing at the distance of two meters from the mockup (See Figure 5). Tests were conducted on the top and at two locations on the side of the IMO diesel engine mockup. The fires consisted of a range of heptane and diesel spray and pan fires. During these tests, the compartment was well ventilated to minimize/eliminate oxygen depletion. A matrix of the planned tests is shown in Table 4. The nozzle spacing and nozzle distance listed as “to be determined” (TBD) were intended to be established as the worst case from the conducted tests.

Table 4. Local Application Evaluation - Planned Tests

Nozzle	Fire Size (MW)	Fire Type	Fire Location (Figure 5)	Nozzle Spacing (m)	Nozzle Distance (m)
FREEBORN	1.0	DIESEL-SPRAY	TOP	N/A	N/A
FREEBORN	1.0	DIESEL-PAN	TOP	N/A	N/A
FREEBORN	1.0	DIESEL-SPRAY	SIDE	N/A	N/A
FREEBORN	1.0	DIESEL-PAN	SIDE	N/A	N/A
FREEBORN	6.0	HEPTANE-SPRAY	SIDE	N/A	N/A
UL/NFPA-15	1.0	DIESEL-SPRAY	TOP	2.0	2.0
UL/NFPA-15	1.0	DIESEL-PAN	TOP	2.0	2.0
UL/NFPA-15	1.0	DIESEL-SPRAY	SIDE	2.0	2.0
UL/NFPA-15	1.0	DIESEL-PAN	SIDE	2.0	2.0
UL/NFPA-15	6.0	HEPTANE-SPRAY	SIDE	2.0	2.0
G-1	1.0	DIESEL-SPRAY	TOP	1.0	1.0
G-1	1.0	DIESEL-PAN	TOP	1.0	1.0
G-1	1.0	DIESEL-SPRAY	TOP	1.0	2.0
G-1	1.0	DIESEL-PAN	TOP	1.0	2.0
G-1	1.0	DIESEL-SPRAY	TOP	1.0	3.0
G-1	1.0	DIESEL-PAN	TOP	1.0	3.0
G-1	1.0	DIESEL-SPRAY	TOP	2.0	1.0
G-1	1.0	DIESEL-PAN	TOP	2.0	1.0
G-1	1.0	DIESEL-SPRAY	TOP	2.0	2.0
G-1	1.0	DIESEL-PAN	TOP	2.0	2.0
G-1	1.0	DIESEL-SPRAY	TOP	2.0	3.0
G-1	1.0	DIESEL-PAN	TOP	2.0	3.0
G-1	1.0	DIESEL-SPRAY	TOP	3.0	1.0
G-1	1.0	DIESEL-PAN	TOP	3.0	1.0
G-1	1.0	DIESEL-SPRAY	TOP	3.0	2.0
G-1	1.0	DIESEL-PAN	TOP	3.0	2.0
G-1	1.0	DIESEL-SPRAY	TOP	3.0	3.0
G-1	1.0	DIESEL-PAN	TOP	3.0	3.0
G-1	6.0	HEPTANE-SPRAY	TOP	TBD	TBD
G-1	1.0	DIESEL-SPRAY	SIDE	1.0	1.0
G-1	1.0	DIESEL-PAN	SIDE	1.0	1.0
G-1	1.0	DIESEL-SPRAY	SIDE	1.0	2.0
G-1	1.0	DIESEL-PAN	SIDE	1.0	2.0
G-1	1.0	DIESEL-SPRAY	SIDE	1.0	3.0
G-1	1.0	DIESEL-PAN	SIDE	1.0	3.0
G-1	1.0	DIESEL-SPRAY	SIDE	2.0	1.0
G-1	1.0	DIESEL-PAN	SIDE	2.0	1.0
G-1	1.0	DIESEL-SPRAY	SIDE	2.0	2.0
G-1	1.0	DIESEL-PAN	SIDE	2.0	2.0
G-1	1.0	DIESEL-SPRAY	SIDE	2.0	3.0
G-1	1.0	DIESEL-PAN	SIDE	2.0	3.0
G-1	1.0	DIESEL-SPRAY	SIDE	3.0	1.0
G-1	1.0	DIESEL-PAN	SIDE	3.0	1.0
G-1	1.0	DIESEL-SPRAY	SIDE	3.0	2.0
G-1	1.0	DIESEL-PAN	SIDE	3.0	2.0

Table 4. Local Application Evaluation - Planned Tests (continued)

Nozzle	Fire Size (MW)	Fire Type	Fire Location (Figure 5)	Nozzle Spacing (m)	Nozzle Distance (m)
G-1	1.0	DIESEL-SPRAY	SIDE	3.0	3.0
G-1	1.0	DIESEL-PAN	SIDE	3.0	3.0
G-1	6.0	HEPTANE-PAN	SIDE	TBD	TBD
G-2	1.0	DIESEL-SPRAY	TOP	1.0	1.0
G-2	1.0	DIESEL-PAN	TOP	1.0	1.0
G-2	1.0	DIESEL-SPRAY	TOP	1.0	2.0
G-2	1.0	DIESEL-PAN	TOP	1.0	2.0
G-2	1.0	DIESEL-SPRAY	TOP	1.0	3.0
G-2	1.0	DIESEL-PAN	TOP	1.0	3.0
G-2	1.0	DIESEL-SPRAY	TOP	2.0	1.0
G-2	1.0	DIESEL-PAN	TOP	2.0	1.0
G-2	1.0	DIESEL-SPRAY	TOP	2.0	2.0
G-2	1.0	DIESEL-PAN	TOP	2.0	2.0
G-2	1.0	DIESEL-SPRAY	TOP	2.0	3.0
G-2	1.0	DIESEL-PAN	TOP	2.0	3.0
G-2	1.0	DIESEL-SPRAY	TOP	3.0	1.0
G-2	1.0	DIESEL-PAN	TOP	3.0	1.0
G-2	1.0	DIESEL-SPRAY	TOP	3.0	2.0
G-2	1.0	DIESEL-PAN	TOP	3.0	2.0
G-2	1.0	DIESEL-SPRAY	TOP	3.0	3.0
G-2	1.0	DIESEL-PAN	TOP	3.0	3.0
G-2	6.0	HEPTANE-SPRAY	TOP	TBD	TBD
G-2	1.0	DIESEL-SPRAY	SIDE	1.0	1.0
G-2	1.0	DIESEL-PAN	SIDE	1.0	1.0
G-2	1.0	DIESEL-SPRAY	SIDE	1.0	2.0
G-2	1.0	DIESEL-PAN	SIDE	1.0	2.0
G-2	1.0	DIESEL-SPRAY	SIDE	1.0	3.0
G-2	1.0	DIESEL-PAN	SIDE	1.0	3.0
G-2	1.0	DIESEL-SPRAY	SIDE	2.0	1.0
G-2	1.0	DIESEL-PAN	SIDE	2.0	1.0
G-2	1.0	DIESEL-SPRAY	SIDE	2.0	2.0
G-2	1.0	DIESEL-PAN	SIDE	2.0	2.0
G-2	1.0	DIESEL-SPRAY	SIDE	2.0	3.0
G-2	1.0	DIESEL-PAN	SIDE	2.0	3.0
G-2	1.0	DIESEL-SPRAY	SIDE	3.0	1.0
G-2	1.0	DIESEL-PAN	SIDE	3.0	1.0
G-2	1.0	DIESEL-SPRAY	SIDE	3.0	2.0
G-2	1.0	DIESEL-PAN	SIDE	3.0	2.0
G-2	1.0	DIESEL-SPRAY	SIDE	3.0	3.0
G-2	1.0	DIESEL-PAN	SIDE	3.0	3.0
G-2	6.0	HEPTANE-SPRAY	SIDE	TBD	TBD

8.1.2 Fire Obstruction Tests

Approximately one hundred fire obstruction water mist tests were planned during this investigation. The approach was to develop a relation between fire extinguishment time and various obstruction parameters (i.e., obstruction size, the distance between the obstruction and the water mist nozzles, and the distance between the fire and the obstruction). Two generic water mist systems were included in this evaluation (both a high and low pressure wide angle system (G1 and G1)). Two obstruction sizes (0.5 m x 1.0 m and 1.0 m x 1.0 m) and three distance parameters (1.0-3.0 m) were included in this evaluation. It was originally intended to conduct these tests at three locations (under one nozzle, between two nozzles and between four nozzles). Due to the uniformity of mist in the space, only one location (between four nozzles) was evaluated. The evaluation was to be conducted primarily against small heptane pan fires (tell-tales) with a selected number of tests repeated against a larger fire (100 kW heptane pan fire). However, the heptane was abandoned in favor of diesel fuel due to the difficulty in extinguishing the heptane fires. During these tests, only the door used to gain access to the compartment was left opened to allow the concentration of mist to increase with time. The planned tests are shown in Table 5.

8.1.3 Scaling Tests

Over fifty total flooding water mist tests were planned during the scaling evaluation. The first set of tests was conducted using two generic water mist systems evaluated during the local application and fire obstruction phases of this investigation. These two systems were evaluated against a variety of fire sizes (0.3-6.0 MW) and vent configurations (vent areas from 1.1 m^2 - 4.0 m^2) to aid in the development of a model to predict extinguishment. The next set of tests focused on identifying the critical fire size for a given vent configuration (smallest fire that could be extinguished). The remaining tests evaluated the effect of application rate on extinguishment time. The planned tests are shown in Table 6.

Table 5. Fire Obstruction Evaluation - Planned Tests

Nozzle	Fire Size (kW)	Fire Type	Location (m)	L_{obs} (m)	D_{noz} (m)	D_{fire} (m)
G-1	5	Heptane-pan	Under One Nozzle	1	1	1
G-1	5	Heptane-Pan	Under One Nozzle	1	1	2
G-1	5	Heptane-Pan	Under One Nozzle	1	1	3
G-1	5	Heptane-Pan	Under One Nozzle	1	2	1
G-1	5	Heptane-Pan	Under One Nozzle	1	2	2
G-1	5	Heptane-Pan	Under One Nozzle	1	3	1
G-1	5	Heptane-Pan	Under One Nozzle	TBD	1	1
G-1	5	Heptane-Pan	Under One Nozzle	TBD	1	2
G-1	5	Heptane-Pan	Under One Nozzle	TBD	1	3
G-1	5	Heptane-Pan	Under One Nozzle	TBD	2	1
G-1	5	Heptane-Pan	Under One Nozzle	TBD	2	2
G-1	5	Heptane-Pan	Under One Nozzle	TBD	3	1
G-1	5	Heptane-Pan	Between Two Nozzles	1	1	1
G-1	5	Heptane-Pan	Between Two Nozzles	1	1	2
G-1	5	Heptane-Pan	Between Two Nozzles	1	1	3
G-1	5	Heptane-Pan	Between Two Nozzles	1	2	1
G-1	5	Heptane-Pan	Between Two Nozzles	1	2	2
G-1	5	Heptane-Pan	Between Two Nozzles	1	3	1
G-1	5	Heptane-Pan	Between Two Nozzles	TBD	1	1
G-1	5	Heptane-Pan	Between Two Nozzles	TBD	1	2
G-1	5	Heptane-Pan	Between Two Nozzles	TBD	1	3
G-1	5	Heptane-Pan	Between Two Nozzles	TBD	2	1
G-1	5	Heptane-Pan	Between Two Nozzles	TBD	2	2
G-1	5	Heptane-Pan	Between Two Nozzles	TBD	3	1
G-1	5	Heptane-Pan	Between Four Nozzles	1	1	1
G-1	5	Heptane-Pan	Between Four Nozzles	1	1	2
G-1	5	Heptane-Pan	Between Four Nozzles	1	1	3
G-1	5	Heptane-Pan	Between Four Nozzles	1	2	1
G-1	5	Heptane-Pan	Between Four Nozzles	1	2	2
G-1	5	Heptane-Pan	Between Four Nozzles	1	3	1
G-1	5	Heptane-Pan	Between Four Nozzles	TBD	1	1
G-1	5	Heptane-Pan	Between Four Nozzles	TBD	1	2
G-1	5	Heptane-Pan	Between Four Nozzles	TBD	1	3
G-1	5	Heptane-Pan	Between Four Nozzles	TBD	2	1
G-1	5	Heptane-Pan	Between Four Nozzles	TBD	2	2
G-1	5	Heptane-Pan	Between Four Nozzles	TBD	3	1
G-1	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-1	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-1	100	Heptane-Pan	TBD	TBD	TBD	TBD

Table 5. Fire Obstruction Evaluation - Planned Tests (continued)

Nozzle	Fire Size (kW)	Fire Type	Location (m)	L_{obs} (m)	D_{noz} (m)	D_{fire} (m)
G-1	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-1	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-1	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-1	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-1	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-1	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-1	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-1	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-2	5	Heptane-Pan	Under One Nozzle	1	1	1
G-2	5	Heptane-Pan	Under One Nozzle	1	1	2
G-2	5	Heptane-Pan	Under One Nozzle	1	1	3
G-2	5	Heptane-Pan	Under One Nozzle	1	2	1
G-2	5	Heptane-Pan	Under One Nozzle	1	2	2
G-2	5	Heptane-Pan	Under One Nozzle	1	3	1
G-2	5	Heptane-Pan	Under One Nozzle	TBD	1	1
G-2	5	Heptane-Pan	Under One Nozzle	TBD	1	2
G-2	5	Heptane-Pan	Under One Nozzle	TBD	1	3
G-2	5	Heptane-Pan	Under One Nozzle	TBD	2	1
G-2	5	Heptane-Pan	Under One Nozzle	TBD	2	2
G-2	5	Heptane-Pan	Under One Nozzle	TBD	3	1
G-2	5	Heptane-Pan	Between Two Nozzles	1	1	1
G-2	5	Heptane-Pan	Between Two Nozzles	1	1	2
G-2	5	Heptane-Pan	Between Two Nozzles	1	1	3
G-2	5	Heptane-Pan	Between Two Nozzles	1	2	1
G-2	5	Heptane-Pan	Between Two Nozzles	1	2	2
G-2	5	Heptane-Pan	Between Two Nozzles	1	3	1
G-2	5	Heptane-Pan	Between Two Nozzles	TBD	1	1
G-2	5	Heptane-Pan	Between Two Nozzles	TBD	1	2
G-2	5	Heptane-Pan	Between Two Nozzles	TBD	1	3
G-2	5	Heptane-Pan	Between Two Nozzles	TBD	2	1
G-2	5	Heptane-Pan	Between Two Nozzles	TBD	2	2
G-2	5	Heptane-Pan	Between Two Nozzles	TBD	3	1
G-2	5	Heptane-Pan	Between Four Nozzles	1	1	1
G-2	5	Heptane-Pan	Between Four Nozzles	1	1	2
G-2	5	Heptane-Pan	Between Four Nozzles	1	1	3
G-2	5	Heptane-Pan	Between Four Nozzles	1	2	1
G-2	5	Heptane-Pan	Between Four Nozzles	1	2	2
G-2	5	Heptane-Pan	Between Four Nozzles	1	3	1
G-2	5	Heptane-Pan	Between Four Nozzles	TBD	1	1
G-2	5	Heptane-Pan	Between Four Nozzles	TBD	1	2

Table 5. Fire Obstruction Evaluation - Planned Tests (continued)

Nozzle	Fire Size (kW)	Fire Type	Location (m)	L_{obs} (m)	D_{noz} (m)	D_{fire} (m)
G-2	5	Heptane-Pan	Between Four Nozzles	TBD	1	3
G-2	5	Heptane-Pan	Between Four Nozzles	TBD	2	1
G-2	5	Heptane-Pan	Between Four Nozzles	TBD	2	2
G-2	5	Heptane-Pan	Between Four Nozzles	TBD	3	1
G-2	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-2	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-2	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-2	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-2	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-2	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-2	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-2	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-2	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-2	100	Heptane-Pan	TBD	TBD	TBD	TBD
G-2	100	Heptane-Pan	TBD	TBD	TBD	TBD

Table 6. Scaling Evaluation - Planned Tests

Nozzle	Fire Size (kW)	Fire Type	Fire Location	Vent (m^2)
G-1	500	Heptane-Spray	TOP	2
G-1	500	Heptane-Spray	TOP	4
G-1	750	Heptane-Spray	TOP	2
G-1	750	Heptane-Spray	TOP	4
G-1	1000	Heptane-Spray	TOP	2
G-1	1000	Heptane-Spray	TOP	4
G-1	1000	Heptane-Pan	TOP	4
G-1	500	Heptane-Spray	SIDE	2
G-1	500	Heptane-Spray	SIDE	4
G-1	750	Heptane-Spray	SIDE	2
G-1	750	Heptane-Spray	SIDE	4
G-1	1000	Heptane-Spray	SIDE	2
G-1	1000	Heptane-Spray	SIDE	4
G-1	1000	Heptane-Pan	SIDE	4

Table 6. Scaling Evaluation - Planned Tests (continued)

Nozzle	Fire Size (kW)	Fire Type	Fire Location	Vent (m^2)
G-1	500	Heptane-Pan	SIDE	TBD
G-1	500	Heptane-Pan	SIDE	TBD
G-1	500	Heptane-Pan	SIDE	TBD
G-1	500	Heptane-Pan	SIDE	TBD
G-1	500	Heptane-Pan	SIDE	TBD
G-2	500	Heptane-Spray	TOP	2
G-2	500	Heptane-Spray	TOP	4
G-2	750	Heptane-Spray	TOP	2
G-2	750	Heptane-Spray	TOP	4
G-2	1000	Heptane-Spray	TOP	2
G-2	1000	Heptane-Spray	TOP	4
G-2	1000	Heptane-Pan	TOP	4
G-2	500	Heptane-Spray	SIDE	2
G-2	500	Heptane-Spray	SIDE	4
G-2	750	Heptane-Spray	SIDE	2
G-2	750	Heptane-Spray	SIDE	4
G-2	1000	Heptane-Spray	SIDE	2
G-2	1000	Heptane-Spray	SIDE	4
G-2	1000	Heptane-Pan	SIDE	4
G-2	500	Heptane-Spray	SIDE	TBD
G-2	500	Heptane-Spray	SIDE	TBD
G-2	500	Heptane-Spray	SIDE	TBD
G-2	500	Heptane-Spray	SIDE	TBD
G-2	500	Heptane-Spray	SIDE	TBD
G-2A	500	Heptane-Spray	SIDE	2
G-2A	500	Heptane-Spray	SIDE	4
G-2A	750	Heptane-Spray	SIDE	2
G-2A	750	Heptane-Spray	SIDE	4
G-2A	1000	Heptane-Spray	SIDE	2
G-2A	1000	Heptane-Spray	SIDE	4
G-2B	500	Heptane-Spray	SIDE	2
G-2B	500	Heptane-Spray	SIDE	4
G-2B	750	Heptane-Spray	SIDE	2
G-2B	750	Heptane-Spray	SIDE	4
G-2B	1000	Heptane-Spray	SIDE	2
G-2B	1000	Heptane-Spray	SIDE	4
G-2C	500	Heptane-Spray	SIDE	2
G-2C	500	Heptane-Spray	SIDE	4
G-2C	750	Heptane-Spray	SIDE	2
G-2C	750	Heptane-Spray	SIDE	4
G-2C	1000	Heptane-Spray	SIDE	2
G-2C	1000	Heptane-Spray	SIDE	4

8.2 Procedures

The tests were initiated from the control room located on the second deck level forward of the test compartment. Prior to the start of the test, the pans were fueled (where applicable), and the compartment ventilation condition set. The video and data acquisition systems were activated, marking the beginning of the test. One minute after the start of the data acquisition system, the fire ignition sequence was initiated, and the compartment was cleared of test personnel. The fires were allowed to freeburn for one minute (two minutes for the obstruction evaluation) prior to mist system activation. The test continued until the fire was extinguished or until 15 minutes after discharge, at which point the mist system was secured. On completion of the test, the space was ventilated to cool the compartment and to remove the remaining agent and products of combustion.

9.0 RESULTS

Over one hundred and fifty tests were conducted during this investigation. The results of the tests will be discussed in the following sections of this report.

9.1 Local Application Test Results

Over fifty local application water mist tests were conducted during this evaluation. The results of the tests conducted on the side of the diesel engine mockup, the tests conducted high in the space and the tests conducted low in the space are shown in Tables 7, 8, and 9 respectively. The capabilities of the water mist systems evaluated during this investigation will be discussed in terms of fire control and fire extinguishment in the following sections.

Table 7. Local Application Test Results (horizontal configuration)

Test	Nozzle	Grid	Nozzle	Pressure	Nozzle	Nozzle	Fire	Fire	Fire	Exting.
1	Horizontal	Side	NFPA-15	7	2	2	1.0	Diesel Spray	Side	No
2	Horizontal	Side	NFPA-15	7	2	1	1.0	Diesel Spray	Side	No
3	Horizontal	Side	G-3	7	2	1	1.0	Diesel Spray	Side	No
4	Horizontal	Side	G-3	7	2	1	1.0	Diesel Pan	Side	2:30
5	Horizontal	Side	NFPA-15	7	2	2	1.0	Diesel Pan	Side	No
6	Horizontal	Side	G-1	7	2	1	1.0	Diesel Pan	Side	1:35
7	Horizontal	Side	G-4	70	2	1	1.0	Diesel Pan	Side	1:45
8	Horizontal	Side	G-2	70	2	1	1.0	Diesel Pan	Side	No
9	Horizontal	Side	G-2	35	2	1	1.0	Diesel Pan	Side	4:09
12	Horizontal	Side	G-2	35	2	1	1.0	Diesel Spray	Side	No
13	Horizontal	Side	G-2	35	2	1	1.0	Diesel Spray	Side	No
14	Horizontal	Side	G-2	35	2	1	6.0	Diesel Spray	Side	No
15	Horizontal	Side	G-4	70	2	1	6.0	Diesel Spray	Side	No
16	Horizontal	Side	G-4	70	2	1	1.0	Diesel Spray	Side	No
17	Horizontal	Side	G-1	7	2	1	1.0	Diesel Spray	Side	No
18	Horizontal	Side	G-1	7	2	1	6.0	Diesel Spray	Side	No
19	Horizontal	Side	G-3	7	2	1	6.0	Diesel Spray	Side	No
20	Horizontal	Side	G-3	7	2	1	1.0	Diesel Spray	Side	No
21	Horizontal	Side	NFPA-15	7	2	2	1.0	Diesel Spray	Side	No
22	Horizontal	Side	NFPA-15	7	2	2	6.0	Diesel Spray	Side	No
23	Horizontal	Side	G-4	70	2	1	6.0	Diesel Spray	Side	2:57
24	Horizontal	Side	G-4	70	2	1	1.0	Diesel Spray	Side	No
25	Horizontal	Side	G-2	35	2	1	6.0	Diesel Spray	Side	No
26	Horizontal	Side	G-2	35	2	1	3.0	Diesel Spray	Side	No
27	Horizontal	Side	G-3	7	2	1	3.0	Diesel Spray	Side	No
28	Horizontal	Side	G-3	7	2	1	6.0	Diesel Spray	Side	No

Table 8. Local Application Test Results (vertical configuration (high))

Test No.	Nozzle Grid	Grid Location	Nozzle	Pressure (bar)	Nozzle Dist (m)	Nozzle Spacing (m)	Fire Size (MW)	Fire Type	Fire Location (Figure 5)	Exting. Time (min:sec)
29	Vertical	High	G-4	70	2	1	1.0	Diesel Spray	Top	0:11
30	Vertical	High	G-4	70	2	1	6.0	Diesel Spray	Top	0:09
31	Vertical	High	G-4	70	2	1	1.0	Diesel Pan	Top	0:05
32	Vertical	High	G-2	35	2	1	1.0	Diesel Pan	Top	0:55
33	Vertical	High	G-2	35	2	1	1.0	Diesel Spray	Top	0:53
34	Vertical	High	G-2	35	2	1	6.0	Diesel Spray	Top	0:21
35	Vertical	High	G-3	7	2	1	1.0	Diesel Spray	Top	0:32
36	Vertical	High	G-3	7	2	1	6.0	Diesel Spray	Top	0:11
37	Vertical	High	G-3	7	2	1	1.0	Diesel Pan	Top	0:09
38	Vertical	High	G-1	7	2	1	1.0	Diesel Pan	Top	0:40
39	Vertical	High	G-1	7	2	1	1.0	Diesel Spray	Top	3:05
40	Vertical	High	G-1	7	2	1	6.0	Diesel Spray	Top	0:22
41	Vertical	High	NFPA-15	7	2	2	1.0	Diesel Spray	Top	No
42	Vertical	High	NFPA-15	7	2	2	6.0	Diesel Spray	Top	No
43	Vertical	High	NFPA-15	7	2	2	1.0	Diesel Pan	Top	No
75	Vertical	High	G-3	7	3	1	1.0	Diesel Spray	Side	No
76	Vertical	High	G-4	70	3	1	1.0	Diesel Spray	Side	No

Table 9. Local Application Test Results (vertical configuration (low))

Test No.	Nozzle Grid	Grid Location	Nozzle	Pressure (bar)	Nozzle Dist (m)	Nozzle Spacing (m)	Fire Size (MW)	Fire Type	Fire Location (Figure 5)	Exting. Time (min:sec)
73	Vertical	Low	G-4	70	2	1	1.0	Diesel Spray	Low	4:24
74	Vertical	Low	G-3	7	2	1	1.0	Diesel Spray	Low	No
111	Vertical	Low	G-4	70	2	1	6.0	Diesel Spray	Low	0:41
112	Vertical	Low	G-4	70	2	1	3.0	Diesel Spray	Low	0:59
113	Vertical	Low	G-4	70	2	1	1.0	Diesel Spray	Low	3:01
114	Vertical	Low	G-4	70	2	1	6.0	Heptane Spray	Low	1:30
115	Vertical	Low	G-4	70	2	1	3.0	Heptane Spray	Low	1:25
116	Vertical	Low	G-4	70	2	1	1.0	Heptane Spray	Low	3:03
117	Vertical	Low	G-4	70	2	1	1.0	Diesel Pan	Low	0:09
118	Vertical	Low	G-4	70	2	1	1.5	Heptane Pan	Low	0:11
119	Vertical	Low	G-2	35	2	1	1.5	Heptane Pan	Low	0:07
120	Vertical	Low	G-2	35	2	1	1.0	Diesel Pan	Low	0:10
121	Vertical	Low	G-2	35	2	1	6.0	Heptane Spray	Low	0:31
122	Vertical	Low	G-2	35	2	1	3.0	Heptane Spray	Low	0:57
123	Vertical	Low	G-2	35	2	1	1.0	Heptane Spray	Low	3:19
124	Vertical	Low	G-2	35	2	1	6.0	Diesel Spray	Low	0:30
125	Vertical	Low	G-2	35	2	1	3.0	Diesel Spray	Low	1:01
126	Vertical	Low	G-2	35	2	1	1.0	Diesel Spray	Low	1:03
127	Vertical	Low	G-3	7	2	1	6.0	Diesel Spray	Low	2:40
128	Vertical	Low	G-3	7	2	1	6.0	Diesel Spray	Low	No
129	Vertical	Low	G-3	18	2	1	6.0	Diesel Spray	Low	0:45
130	Vertical	Low	G-3	18	2	1	3.0	Diesel Spray	Low	1:15
131	Vertical	Low	G-3	18	2	1	1.0	Diesel Spray	Low	3:35
132	Vertical	Low	G-3	18	2	1	6.0	Heptane Spray	Low	0:51

Table 9. Local Application Test Results (vertical configuration (low)) (continued)

Test No.	Nozzle Grid	Grid Location	Nozzle	Pressure (bar)	Nozzle Dist (m)	Nozzle Spacing (m)	Fire Size (MW)	Fire Type	Fire Location (Figure 5)	Exting. Time (min:sec)
133	Vertical	Low	G-3	18	2	1	3.0	Heptane Spray	Low	2:04
134	Vertical	Low	G-3	18	2	1	1.0	Heptane Spray	Low	1:20
135	Vertical	Low	G-3	18	2	1	1.0	Diesel Pan	Low	0:07
136	Vertical	Low	G-3	18	2	1	1.0	Diesel Pan	Low	0:09
137	Vertical	Low	G-3	18	2	1	1.5	Heptane Pan	Low	0:09
138	Vertical	Low	G-3	18	2	1	1.5	Heptane Pan	Low	0:12
139	Vertical	Low	G-1	7	2	1	1.5	Heptane Pan	Low	0:35
140	Vertical	Low	G-1	7	2	1	1.0	Diesel Pan	Low	0:06
141	Vertical	Low	G-1	7	2	1	6.0	Heptane Spray	Low	1:21
142	Vertical	Low	G-1	7	2	1	3.0	Heptane Spray	Low	2:46
143	Vertical	Low	G-1	7	2	1	1.0	Heptane Spray	Low	No
144	Vertical	Low	G-1	7	2	1	6.0	Diesel Spray	Low	0:35
145	Vertical	Low	G-1	7	2	1	3.0	Diesel Spray	Low	1:00
146	Vertical	Low	G-1	7	2	1	1.0	Diesel Spray	Low	2:14
147	Vertical	Low	G-4	70	2	2	6.0	Heptane Spray	Low	No
148	Vertical	Low	G-6	70	2	2	6.0	Heptane Spray	Low	No
149	Vertical	Low	G-6	70	2	2	6.0	Diesel Spray	Low	No
150	Vertical	Low	G-6	70	2	2	6.0	Diesel Spray	Low	0:50
151	Vertical	Low	G-6	70	2	2	3.0	Diesel Spray	Low	0:48
152	Vertical	Low	G-6	70	2	2	1.0	Diesel Spray	Low	1:32
153	Vertical	Low	G-6	70	2	2	1.0	Diesel Spray	Low	2:55
154	Vertical	Low	G-6	70	2	2	1.0	Diesel Spray	Low	2:53
155	Vertical	Low	G-6	70	2	2	1.0	Diesel Spray	Low	2:51
156	Vertical	Low	G-6	70	2	2	6.0	Heptane Spray	Low	0:46
157	Vertical	Low	G-6	70	2	2	3.0	Heptane Spray	Low	1:05
158	Vertical	Low	G-6	70	2	2	1.0	Heptane Spray	Low	1:37

9.1.1 Extinguishment Analysis

In general, the pan fires (both heptane and diesel) evaluated during these tests were easily extinguished by a majority of the local application water mist systems independent of the fire location. Nineteen of the twenty-one pan fires conducted in this evaluation were extinguished. These pan fires were typically extinguished in less than thirty seconds, with the heptane pan fires usually requiring about ten seconds longer to extinguish than the diesel fires. The spray fires, however, were more difficult to extinguish and were only extinguished about sixty percent of the time. Only forty-two of the sixty-eight spray fires were extinguished during this evaluation. During tests of spray fires that were not extinguished, the fires would continue to burn in areas of lower mist concentrations (i.e., between mist nozzles). The low concentration areas were visually observed during mist discharges with and without the fires. The larger spray fires were easier to extinguish than smaller spray fires. This may be related to the higher entrainment rates characteristic of larger fires (re-entrainment of combustion gases and steam). Heptane spray fires were also observed to be slightly more difficult to extinguish than diesel spray fires. These characteristics are similar to those observed during the open roof vent tests conducted during the previous phase of this investigation [3].

The water mist systems evaluated during these tests had better capabilities when the nozzles were installed above the fire spraying downward as opposed to along side the fire spraying horizontally. This becomes apparent by comparing the results of the spray fire tests conducted on the top and on the side of the diesel engine mockup. With the nozzles directed downward, the systems were capable of extinguishing over 90 percent of the spray fires as compared to only five percent using a horizontal attack. By spraying directly downward on top of the flame, a portion of the vitiated gases and steam may be re-directed back into the combustion zone of the flame.

When the local application water mist systems were installed above the hazard/object being protected, the water mist system demonstrated significant extinguishment capabilities. With this installation (one meter nozzle spacing with nozzles installed two meters from the hazard), all of the generic water mist systems were capable of extinguishing all of the unobstructed diesel and heptane spray fires in approximately three minutes or less. The larger fires (3.0 MW and 6.0 MW) were typically extinguished in approximately one minute while the smaller fires (1.0 MW) required almost three minutes to extinguish. The trends in extinguishment times for the low level vertical attack local application systems are shown in Figure 9.

It was originally intended to conduct a series of tests to evaluate how the extinguishment capabilities of the systems varied with distance from the fire and water mist nozzle spacing. It became apparent early in the investigation that any areas of lower/inadequate mist concentration (and possibly lower velocity) would prevent the system from extinguishing a spray fire. To prevent a large number of failures, these generic systems were evaluated in a configuration producing a uniform mist concentration and adequate velocity. The typical configuration consisted of nozzles installed with a one-meter nozzle spacing at a distance of 2.0 m from the fire. Greater nozzle spacings resulted in holes in the spray patterns (areas of lower mist concentration and or inadequate pattern coverages) and poor extinguishment capabilities. During a series of scoping tests not reported in this document, it was observed that if the nozzles were installed closer to the fire, the fire would extend through the mist/nozzles and burn on the backside (no mist) of the nozzle grid. Greater distances between the local application system and the fire resulted in poor mist penetration into the combustion zone allowing the fire to continue to burn.

Due to the observed limitations of the candidate local application water mist systems, the obstruction evaluation was also eliminated. It can be assumed that even small obstructions have the potential to prevent the extinguishment of a fire using a local application water mist system.

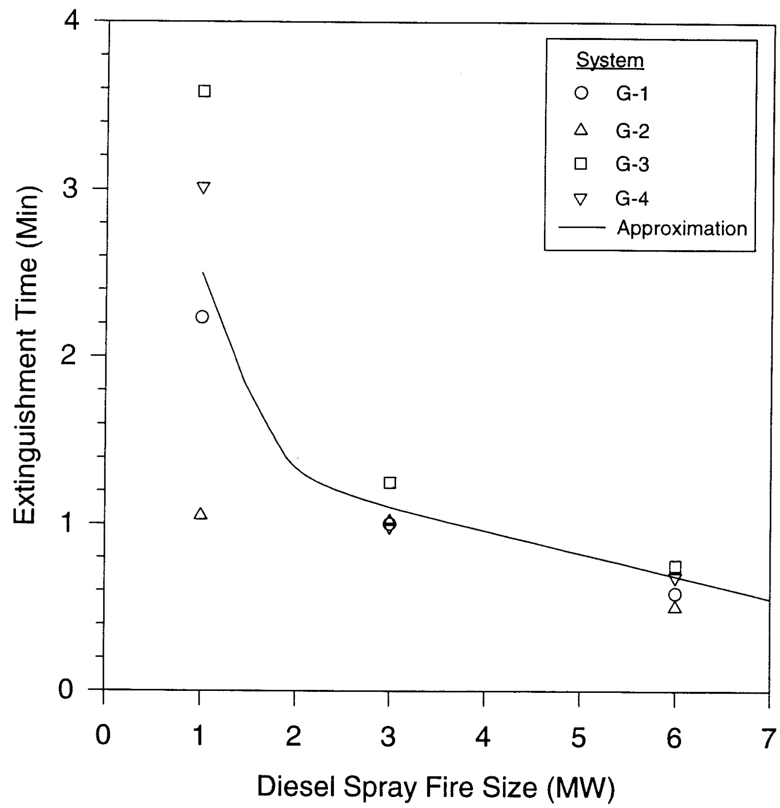


Figure 9. Local application system extinguishment times

The generic water mist systems evaluated during this investigation all produce droplets with $Dv_{90's}$ less than 500 microns. Installed with a nominal 1.0 m nozzle spacing, each system produced a mist concentration on the order of 50-100 g/m^3 at a velocity of over 1.0 m/s measured 2.0 m from the nozzle. Based on these system characteristics, and on the results of the local application tests conducted with the nozzles installed above the fire, it appears that a local application water system that produces a uniform mist concentration greater than 50 g/m^3 at a velocity of over 1.0 m/s at the fire location, should be capable of extinguishing a wide range of unobstructed spray and pan fires. Identification of a critical mist concentration and velocity required to extinguish a fire was beyond the scope of this investigation and requires additional research.

The downward spraying local application water mist system was evaluated at two locations; in the overhead of the space (high) as shown in Figure 10A and at a lower elevation (low) as shown in Figure 10B. These results are shown in Table 10. Although the compartment was well ventilated, a thin upper layer was still produced. When the nozzles were installed high in the space, the capabilities of the candidate local application water mist systems were found to increase as a result of the entrainment of vitiated gases (upper layer) into the mist spray patterns. The entrainment of vitiated gases into the water spray patterns of the nozzles produced localized oxygen depletion effects in the protected area. The entrainment of the vitiated gases significantly increased the extinguishment capabilities of the system and reduced the extinguishment times by an order of magnitude.

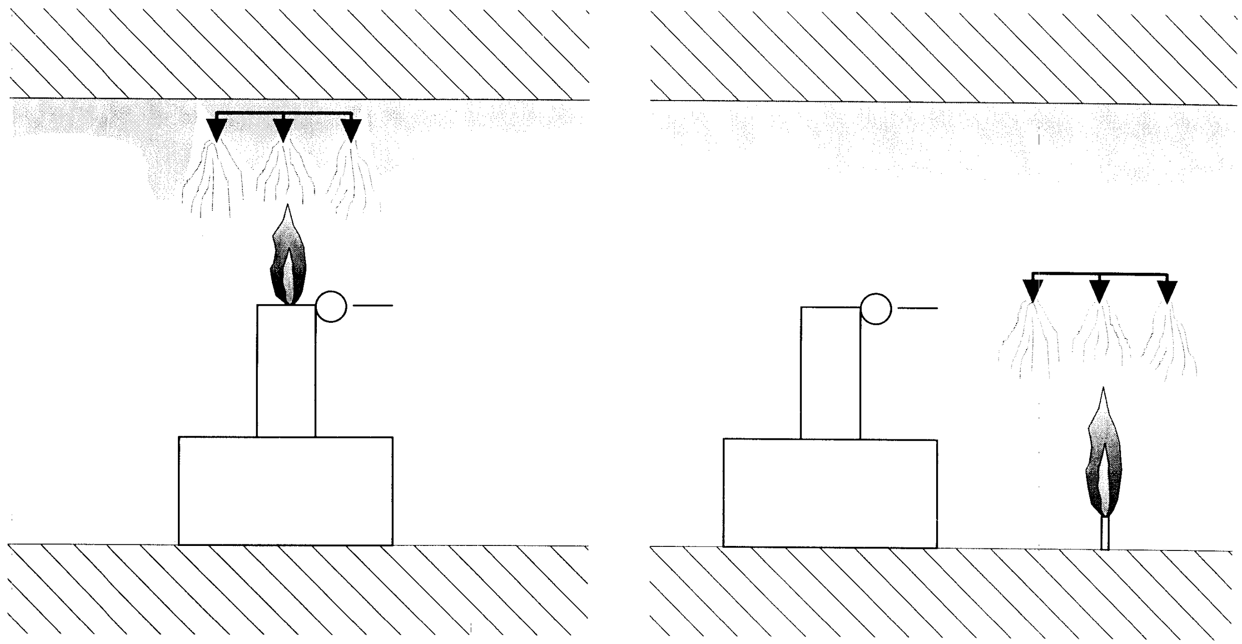


Figure 10A · Overhead Local Application System

Figure 10B · Low Level Local Application System

Figure 10. Vertical attack local application water mist systems

Table 10. Local Application Test Results (location evaluation)

Test No.	Nozzle Grid	Grid Location	Nozzle	Pressure (bar)	Nozzle Dist (m)	Nozzle Spacing (m)	Fire Size (MW)	Fire Type	Fire Location (Figure 5)	Exting. Time (min:sec)
29	Vertical	High	G-4	70	2	1	1.0	Diesel Spray	Top	0:11
73	Vertical	Low	G-4	70	2	1	1.0	Diesel Spray	Low	4:24
76	Vertical	High	G-4	70	3	1	1.0	Diesel Spray	Side	No
35	Vertical	High	-3	7	2	1	1.0	Diesel Spray	Top	0:32
74	Vertical	Low	G-3	7	2	1	1.0	Diesel Spray	Low	No
75	Vertical	High	G-3	7	3	1	1.0	Diesel Spray	Side	No

The system that exhibited superior extinguishment capabilities throughout this test series was the wide angle, high pressure, single fluid system (G-4). This system produced the fastest extinguishment times for a majority of the tests and was the only system to extinguish the 6.0 MW diesel spray fire with the nozzles spraying horizontally. The system producing the poorest results was the UL-approved NFPA-15 water spray system which was only capable of extinguishing one of the six test fires.

9.1.2 Control Analysis

All five local application water mist systems evaluated during this test series dramatically reduced the severity of the thermal conditions in the space.

The effect that water mist from a local application system has on the thermal conditions in the space is shown in Table 11. The analysis was conducted on the fires that were not extinguished by the water mist systems and addresses the heat release rate of the fire, energy absorbed by the mist, and the effects on radiation. Details of the analysis are described in the following paragraphs.

The theoretical heat release rate of the fire was calculated using the fuel flow rate and the heat of combustion of the fuel, assuming complete combustion. The estimated heat release rate

Table 11. Control Evaluation Table (side)

Test No.	Q_{Fire} Theo. (MW)	Q_{Fire} Est. (MW)	Fire Size Reduction (%)	Nozzle	O_2 (%)	T_{gas} (BC)	T_{plate} (BC)	THF (kW/m^2)	Q_{gas} (kW)	Q_{bound} (kW)	Q_{mist} (kW)	Energy Abs. by Mist (%)	$Q_{R\ Pre}$ (kW/m^2)	$Q_{R\ Mist}$ (kW/m^2)	Rad. Atten. (%)
10	1.4	1.5	0	Free Burn	18.2	160	170	2.7	513	800	NA	NA	3	N/A	0
12	1.4	1.4	0	G-2	18.3	112	117	0.7	330	200	870	62	3	0.8	73
13	1.4	1.4	0	G-2	18.3	122	132	0.7	369	200	831	59	3	1.0	67
14	6.3	4.9	22	G-2	12.0	351	380	3.2	1240	960	2700	55	10	2.2	78
15	6.3	3.3	48	G-4	14.8	265	225	1.0	912	300	2088	63	10	0.5	95
16	1.4	1.45	0	G-4	18.3	130	100	1.4	399	420	631	44	3	0.3	90
17	1.4	1.36	0	G-1	18.5	134	120	0.8	414	240	706	52	3	1.0	67
18	6.3	4.45	29	G-1	12.8	342	325	3.0	1205	880	2365	53	10	1.3	87
19	6.3	4.34	31	G-3	13.0	360	350	5.4	1273	1600	1467	34	10	1.3	87
20	1.4	1.5	0	G-3	18.2	152	130	1.2	482	360	658	44	3	0.6	80
21	1.4	1.55	0	NFPA-15	18.0	116	120	0.8	345	250	955	62	3	0.6	80
22	6.3	3.70	41	NFPA-15	14.2	300	425	2.3	1045	700	1955	53	10	1.6	84
23	6.3	Extinguished		G-4											
24	1.4	1.4	0	G-4	18.2	80	85	0.8	209	250	941	67	3	0.2	93
25	6.3	5.7	10	G-2	10.2	350	460	4.0	1235	1200	3265	57	10	3.0	70
26	3.0	2.9	0	G-2	15.7	200	255	1.5	665	450	1785	62	4.8	1.8	63
27	3.0	2.7	10	G-3	16.0	170	195	1.2	551	350	1799	67	4.8	1.0	79
28	6.3	4.23	33	G-3	13.2	265	320	1.6	912	490	2828	67	10	1.0	90

was determined based on oxygen calorimetry in the space. The fire size was estimated based on the oxygen concentration and mass flow rate of the gases through the compartment using the following equation:

$$\dot{Q}_{est} = \dot{M}_{gas} \Delta \chi_{O_2} \left(\frac{MW_{O_2}}{MW_{air}} \right) \Delta H_{R_{O_2}} \tag{1}$$

where $\dot{Q}_{est}$ = estimated fire size,

$\dot{M}_{gas}$ = mass flow rate of gas/air,

$\Delta\chi_{O2}$ = difference in oxygen concentration (mole fraction) between the stack gases and ambient air,

MW_{O2} = molecular weight of oxygen,

MW_{air} = molecular weight of air, and

ΔH_{RO2} = heat of reaction of oxygen.

The mass flow rate of gases through the compartment was determined using a velocity probe located in the supply air duct.

The results of the fire size analysis are shown in Table 11. In short, for the small fires (1.0 - 3.0 MW), the fire size was unaffected by the application of mist. This is shown by the similarity between the theoretical and estimated fire sizes. For the large fires (6.0 MW), the fire size was reduced on the order of 10-50 percent depending on the system. The difference between the estimated and theoretical fire sizes quantifies the amount of unburned fuel discharged by the spray fire nozzle during the large fire tests. The amount of energy absorbed by the mist was based on the following equation:

$$\dot{Q}_{fire} = \dot{Q}_{boundary} + \dot{Q}_{gas} + \dot{Q}_{mist} \tag{2}$$

where $\dot{Q}_{fire}$ = energy released by the fire,

$\dot{Q}_{boundary}$ = energy absorbed by the boundary,

$\dot{Q}_{gas}$ = energy absorbed by the gases flowing through the compartment, and

$\dot{Q}_{mist}$ = energy absorbed by the mist.

The energy released by the fire ($\dot{Q}_{fire}$) was calculated using Equation (1). The energy absorbed by the boundary ($\dot{Q}_{boundary}$) was calculated using the average total heat flux measured at the bulkhead (average of the four installed in the compartment) multiplied by the surface area of the compartment (walls, ceiling, and floor). The energy absorbed by the gas was calculated based on the mass flow rate of gas through the compartment and the temperature of the gases leaving the compartment using the following equation:

$$\dot{Q}_{gas} = \dot{M}_{gas} C_p \Delta T$$

where $\dot{Q}_{gas}$ = energy absorbed by the gas/air,

$\dot{M}_{gas}$ = mass flow rate of gas/air,

C_p = specific heat of the gas, and

ΔT = the difference in the temperature of the gas entering (T_{amb}) and exiting (T_{stack}) the compartment.

The gas temperatures were measured using five thermocouples installed just below the overhead of the space. The average of these five thermocouples produced similar values as those measured using the plate thermometers.

The amount of energy absorbed by the mist ($Q_{mist}/Q_{fire\ (est)}$ x 100) is shown in Table 11. The mist typically absorbed between 30 and 70 percent of the energy release by the fire. The energy absorbed by the fire appears somewhat random in nature, does not appear to be a function of fire size, and it appears somewhat uniform between the systems evaluated during this test series.

The radiation attenuated by the mist was determined using the radiometers adjacent to the fire location. The percent of the radiation attenuated is the ratio of the radiation measured during the preburn and after mist discharge. $((Q_{RPre} - Q_{Rmist})/Q_{RPre} \times 100)$. The water mist systems typically attenuated between 60 and 90 percent of the radiation released by the fire.

In summary, when the fires were not extinguished by the local application water mist systems, the thermal conditions in the space were dramatically reduced. It was shown during these tests that between 30 and 70 percent of the energy released by the fire was absorbed by the mist. The radiation to adjacent objects was also reduced by 60 to 90 percent. These reductions in the thermal conditions produced by the fire should reduce fire damage and aid in manual intervention.

9.2 Fire Obstruction Test Results

Thirty-five fire obstruction tests were conducted during this evaluation. The results of these tests are shown in Table 12.

The evaluation was conducted against small diesel pan fires (5 kW - tell-tale fires) with a selected number of tests repeated against a larger fire (100 kW diesel pan fire). It was originally intended to use heptane as the test fuel, but the small heptane fires could not be extinguished by the total flooding water mist systems evaluated during this test series.

It was also originally intended to conduct these tests with the fire obstruction apparatus located under one nozzle, between two nozzles, and between four nozzles. During the setup and shakedown of the fire obstruction apparatus, it was determined by the similarity in extinguishment times between the three locations that the mist in the compartment was relatively uniform, eliminating the need to conduct these tests at all three locations. The mist uniformity was attributed to the combination of the wide spray patterns of the water mist nozzles and narrow nozzle spacings of the system designs.

Table 12. Fire Obstruction Evaluation Results

Test No.	Nozzle	Pressure (bar)	Test Fire	Fire Elevation	Obstruction Elevation	Obstruction Size	Exting. Time
77	G-3	7	Heptane-Pan	1.00	N/A	0.00	No
78	G-3	7	Heptane-Pan	2.00	N/A	0.00	No
79	G-3	7	Diesel-Pan	1.00	N/A	0.00	0:12
80	G-3	7	Diesel-Pan	1.00	2.00	0.50	0:17
81	G-3	7	Diesel-Pan	1.00	2.00	1.00	0:31
82	G-3	7	Diesel-Pan	1.00	3.00	0.50	0:12
83	G-3	7	Diesel-Pan	1.00	3.00	1.00	0:13
84	G-3	7	Diesel-Pan	1.00	4.00	0.50	0:11
85	G-3	7	Diesel-Pan	1.00	4.00	1.00	0:08
86	G-3	7	Diesel-Pan	2.00	4.00	1.00	0:10
87	G-3	7	Diesel-Pan	2.00	4.00	0.50	0:07
88	G-3	7	Diesel-Pan	3.00	4.00	0.50	0:14
89	G-3	7	Diesel-Pan	3.00	4.00	1.00	0:44
90	G-3	7	Diesel-Pan	2.00	3.00	0.50	0:08
91	G-3	7	Diesel-Pan	2.00	3.00	1.00	0:29
92	G-4	70	Diesel-Pan	2.00	N/A		0:06
93	G-4	70	Diesel-Pan	2.00	3.00	0.50	0:15
94	G-4	70	Diesel-Pan	2.00	3.00	1.00	0:29
95	G-4	70	Diesel-Pan	2.00	4.00	0.50	0:07
96	G-4	70	Diesel-Pan	2.00	4.00	1.00	0:07
97	G-4	70	Diesel-Pan	3.00	4.25	1.00	0:06
98	G-4	70	Diesel-Pan	3.00	4.00	1.00	0:08
99	G-4	70	Diesel-Pan	3.00	3.75	1.00	0:17
100	G-4	70	Diesel-Pan	3.00	3.50	1.00	0:23
101	G-4	70	Diesel-Pan	3.00	3.25	1.00	0:33
102	G-4	70	Diesel-Pan	3.00	3.15	1.00	0:33
103	G-4	70	Diesel-Pan	1.00	3.00	1.00	0:14
104	G-4	70	Diesel-Pan	1.00	3.00	0.50	0:12
105	G-4	70	Heptane-Pan	1.00	3.00	0.00	No
106	G-4	70	Diesel-Pan	1.00	2.00	0.50	0:17
107	G-4	70	Diesel-Pan	1.00	2.00	1.00	0:29
108	G-4	70	Diesel-Pan	1.00	1.75	1.00	0:39
109	G-4	70	Diesel-Pan	1.00	1.50	1.00	0:35
110	G-4	70	Diesel-Pan	1.00	1.25	1.00	No

* Refer to Figure 7

In general, the diesel fuel fires were easily extinguished as compared to heptane fires. The ability of mist to reduce the flame radiation back to the fuel surface as well as to cool the fuel surface was apparent during these tests. The candidate water mist systems were capable of extinguishing over 90 percent of these fires independent of the degree fire obstruction and the fire preburn time. The fires were ignited using a propane torch and allowed to pre-burn until the fuel in the pan began boiling. In a majority of the tests, after the fires were extinguished, the fuel was still boiling in the pan.

9.2.1 Obstruction Size and Discharge Effects

The obstructions consisted of two steel plates of different sizes (1.0 m x 0.5 m and 1.0 m x 1.0 m). The plates were positioned at various locations above the fire and the distance between the fire and the water mist nozzles was also varied.

As expected, the larger the obstruction, the greater the impact the obstruction had on the fire extinguishment capabilities of the system (Figure 11). The addition of the small obstruction above the fire approximately doubled the extinguishment time as compared to the unobstructed case. As the distance between the obstruction and the fire was increased, the effect of the obstruction was reduced and the extinguishment times approached the value observed for the unobstructed fire test.

The large obstruction produced the same trend, but to a greater degree. The large obstruction approximately tripled the extinguishment time when installed one meter above the fire and had a reduced effect as the distance between the fire and the obstruction was increased.

Throughout this obstruction evaluation, the extinguishment times for the fires located high in the space were less than those conducted at lower elevations. Besides the obvious mist shadow effects, which are a function of the spray pattern of the nozzle (cone angle), this may also be related to the velocity of the mist at this location. The velocity of mist near the nozzles is

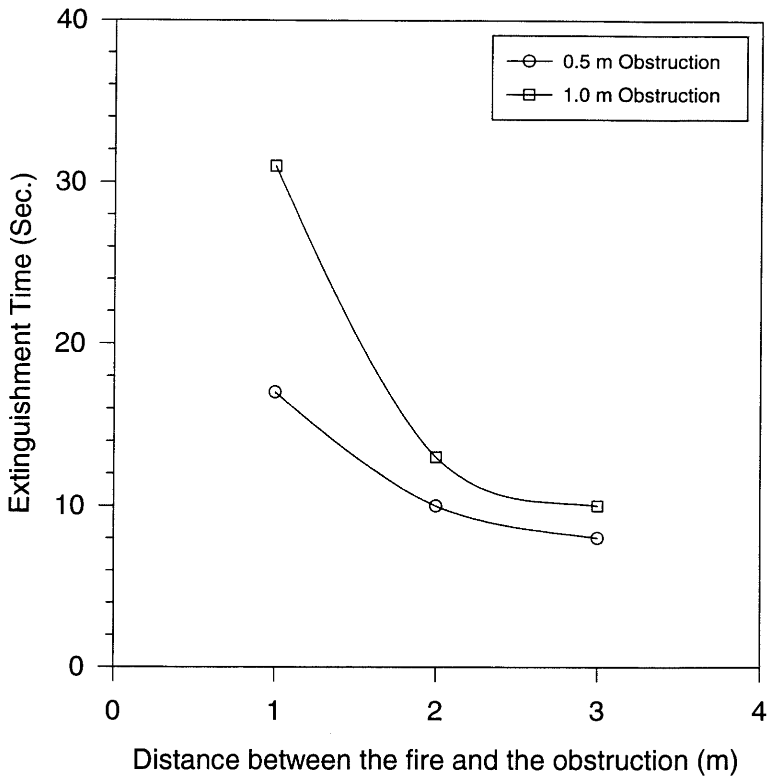


Figure 11. Obstruction size and discharge evaluation (System: G1, Fire Elevation: 1m)

typically higher than elsewhere in the compartment. The higher velocity may allow the mist to flow more easily around the obstruction and reach the fire.

To further challenge the candidate systems, the evaluation was conducted with distance between the obstruction and the fire reduced to below one meter. The evaluation was conducted with the fire located one, two, and three meters above the deck. The results of these tests are plotted in Figure 12 for two fire evaluations (1.0 m and 3.0 m).

As shown in this figure the trends observed for the greater distances continued to prevail. As the distance between the obstruction and the fire was reduced, the extinguishment times steadily increased until the fire could not be extinguished. This occurred at a distance less than a quarter meter separation. The degree of obstruction required to prevent these small fires from being extinguished was higher than originally anticipated. In short, the obstruction sizes and distances originally selected for evaluation did not pose a significant challenge to the candidate water mist systems.

9.3 Scaling Evaluation Results

Thirty scaling evaluation tests were conducted during this test series. The results of these tests are shown in Tables 13 and 14.

The approach consisted of conducting a series of tests with varying fire sizes and ventilation conditions (various size vent openings) to evaluate their effect on extinguishment capabilities of the systems and on the resulting conditions in the compartment (gas concentrations and temperatures). The information served to validate and refine a steady state extinguishment model developed during the initial investigation [3].

The model is based on conservation of energy and mass and requires the following input parameters: fire size, compartment geometry, vent area, and water mist system flow rate. From

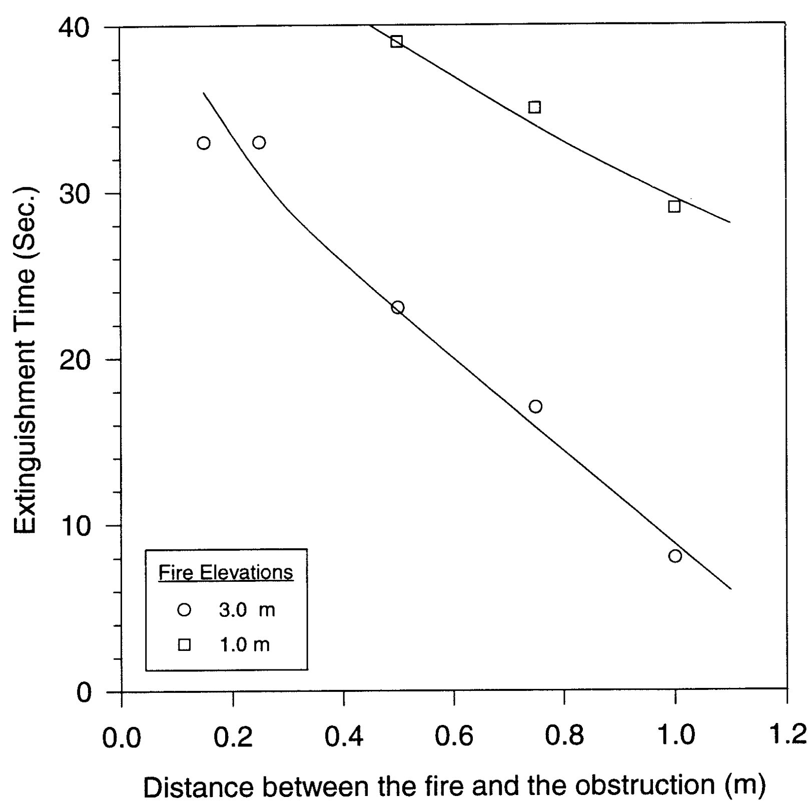


Figure 12. Obstruction distance and elevation evaluation (high pressure)

Table 13. Scaling Test Results (critical fire size evaluation)

Test No.	Nozzle	Pressure (bar)	Flow Rate kg/s	Fire Size (MW)	Fire Type	Vent Area (m^2)	Exting. Time (min:sec)	Steady State Temp (EC)	Steady State O_2 Conc. (%)	Adjusted O_2 Conc. (%)
44	G-1	7	6.8	1	Spray	4	4:55	50	16.2	14.2
45	G-1	7	6.8	1	Spray	2	4:11	51	16.6	14.4
46	G-1	7	6.8	1	Spray	1.1	3:23	52	16.9	14.6
47	G-1	7	6.8	0.85	Spray	1.1	6:35	50	16.3	14.3
48	G-1	7	6.8	0.85	Spray	2	6:32	49	16.4	14.5
49	G-1	7	6.8	0.85	Spray	4	9:08	50	16.2	14.2
50	G-1	7	6.8	0.6	Spray	1.1	9:04	48	16.9	15.0
51	G-1	7	6.8	0.6	Spray	2	9:46	46	16.5	14.8
52	G-1	7	6.8	0.6	Spray	4	No	44	17.3	15.8
53	G-1	7	6.8	0.3	Spray	2	No	35	17.0	16.1
54	G-1	7	6.8	1	Pan	4	13:12	42	17.0	15.6
55	G-2	70	5.0	1	Spray	4	4:00	50	17.8	15.6
56	G-2	70	5.0	1	Spray	4	5:24	50	17.0	14.9
57	G-2	70	5.0	1	Spray	2	5:26	53	16.4	14.0
58	G-2	70	5.0	1	Spray	1.1	3:54	55	18.0	15.1
59	G-2	70	5.0	1	Spray	4	6:17	48	16.5	14.6
60	G-2	70	5.0	0.85	Spray	1.1	5:24	52	17.0	14.7
61	G-2	70	5.0	0.85	Spray	2	5:53	50	17.0	14.9
62	G-2	70	5.0	0.85	Spray	4	5:42	49	17.4	15.3
63	G-2	70	5.0	0.6	Spray	1.1	6:38	50	17.4	15.3
64	G-2	70	5.0	0.6	Spray	2	9:19	48	16.7	14.8

Table 14. Scaling Test Results (reduced water flow rate evaluation)

Test No.	Nozzle	Pressure (bar)	Flow Rate kg/s	Fire Size (MW)	Fire Type	Vent Area (m^2)	Exting. Time (min:sec)	Steady State Temp (EC)	Steady State O_2 Conc. (%)	Adjusted O_2 Conc. (%)
65	G-2	35	3.5	0.85	Spray	1.1	3:40	52	17.7	15.3
66	G-2	35	3.5	0.85	Spray	2	4:28	51	17.2	15.0
67	G-2	35	3.5	0.85	Spray	4	5:08	50	17.8	15.6
68	G-5	35	1.5	0.85	Spray	1.1	5:23	58	16.8	13.7
69	G-5	35	1.5	0.85	Spray	2	6:06	56	16.6	13.8
70	G-5	35	1.5	0.85	Spray	4	6:24	55	16.4	13.8
71	G-5	35	1.5	3	Spray	4	2:25	70	18.9	13.9
72	G-5	35	1.5	3	Spray	4	1:01	69	18.0	13.6

these conditions, the model can predict the steady state compartment temperature and steady state oxygen concentrations in the space. The steady state oxygen concentrations can be used to determine the smallest fire (critical fire size) that will adequately reduce the oxygen concentration in the space below the Limiting Oxygen Index (LOI) of typical fuels and result in extinguishment.

The steady state temperatures measured during these tests are listed in Tables 13 and 14. The steady state temperatures ranged from 35 to 55EC, depending on the fire size and ventilation condition (vent size). In general, for a fixed fire size (i.e., 1.0 MW), increasing the vent area from 1.1 m^2 to 4.0 m^2 reduced the steady state compartment temperature by three or four degrees. For a fixed vent area (i.e., 1.1 m^2), reducing the fire size reduced the steady state compartment temperature approximately one degree Celsius for each 100 kW reduction in heat release rate.

The effect of reducing the water mist system flow rate on the steady state compartment temperatures is shown in Table 14. For a fixed fire size (i.e., 0.85 MW) and a fixed vent area (i.e., 1.1 m^2), reducing the water flow rate typically increases the steady state compartment temperature by two degrees Celsius for each one kilogram per second reduction in water mist system flowrate. This is shown by the temperatures measured during Test # 65 and Test # 68.

The model was used to accurately predict the steady state compartment temperatures for the tests conducted during this evaluation. Shown in Figure 13 are the predicted and measured steady state compartment temperatures for the tests conducted with the narrow angle low pressure water mist system (Nozzle G-1). The temperatures predicted by the model are within three degrees Celsius of those recorded during these tests. The same agreement was observed for the other systems/nozzles included in this evaluation.

The oxygen concentrations measured in the compartment during the extinguishment of the fires are shown in Tables 13 and 14. The oxygen concentrations typically ranged from 16-18 percent by volume (dry). The measured concentrations were adjusted to include water vapor, assuming that the gases were saturated, and are also shown in Tables 13 and 14. The measured and adjusted oxygen concentrations are plotted in Figure 14 as a function of compartment temperature. These data suggest that a conservative estimate for the LOI of heptane using the products of combustion and water vapor as the diluent is approximately 14 percent by volume. All of the fires conducted during this evaluation were extinguished when the adjusted oxygen concentrations approached 14 percent by volume. This compares favorably to the results found in the literature [11] and in the previous phase of this investigation [3].

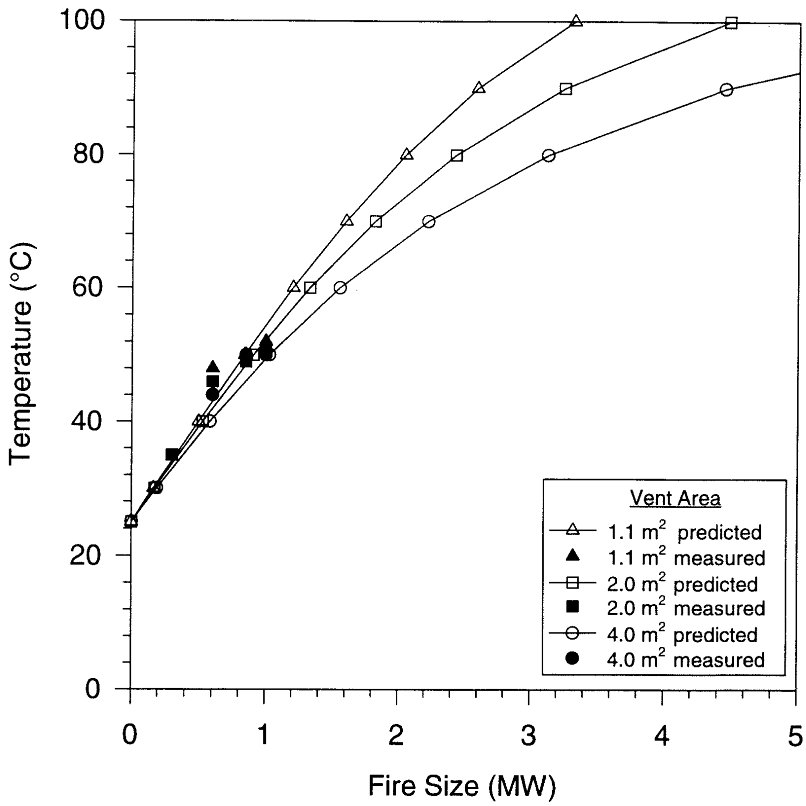


Figure 13. Steady state compartment temperatures

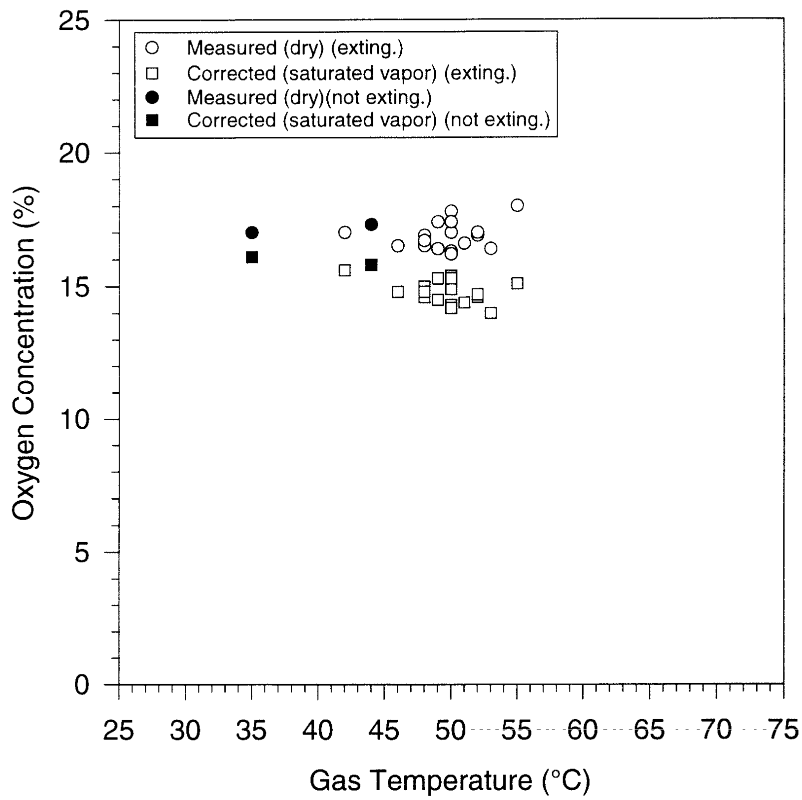


Figure 14. Adjusted oxygen concentrations

The model was also used to predict the steady state oxygen concentrations for the tests conducted during this evaluation. An example of these predictions is shown in Figure 15. A comparison between the predicted and measured oxygen concentrations is inappropriate due to the fact that a majority of these fires were extinguished before steady state conditions were achieved. However, the predicted oxygen concentration can be validated based on the prediction of a critical fire size.

Assuming the LOI for heptane using water vapor and combustion products as the diluent is 14 percent by volume, the critical fire size for the three ventilation conditions evaluated during these tests can be determined for the narrow angle low pressure water mist system from Figure 15. The critical fire size is defined as the smallest fire that will reduce the oxygen concentration in the compartment (due to both consumption and dilution) below the LOI of the fuel. It is also the fire size that the extinguishment times measured during these tests exponentially approach as the fire size is reduced.

The extinguishment times are plotted as a function of fire size for the narrow angle low pressure water mist system evaluated in a compartment having a 2.0 m^2 vent opening (Figure 16). Also shown in this figure is the critical fire size as determined from Figure 15. Based on this figure, the model was able to accurately predict the critical fire size, which also supports the accuracy of the predicted steady state oxygen concentration.

Future work is required to develop a transient model to predict extinguishment time as well as the temperature and gas concentration histories in the compartment. The steady state model shows promise for this development and should serve as the foundation for the transient model.

9.4 Compartment Environment Evaluation Discussion

The approach to evaluate the environmental conditions in the compartment during mist discharge was to provide additional instrumentation to measure the effect on visibility, thermal

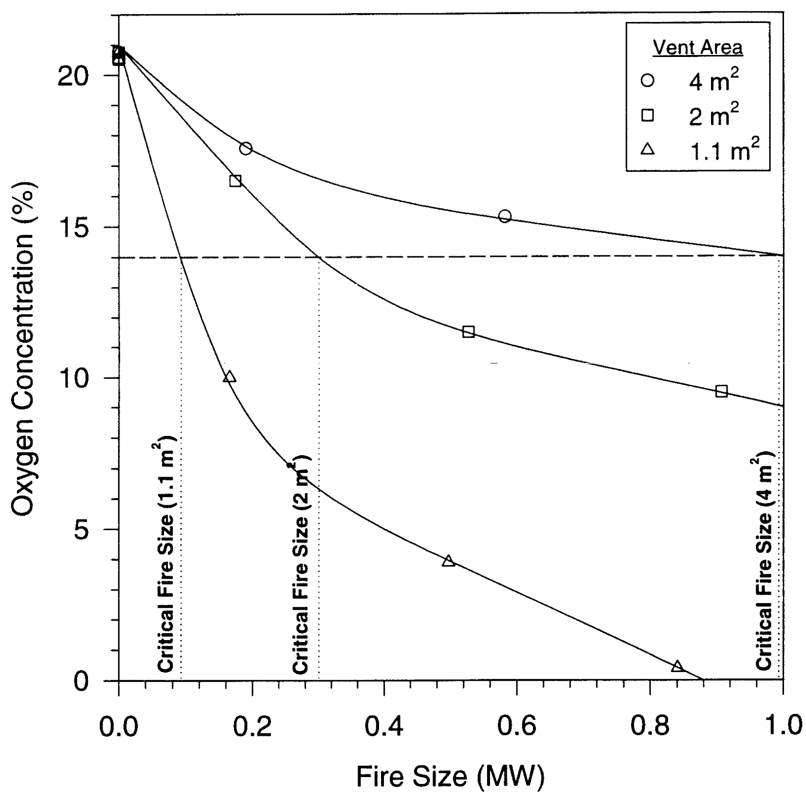


Figure 15. Predicted steady state oxygen concentrations

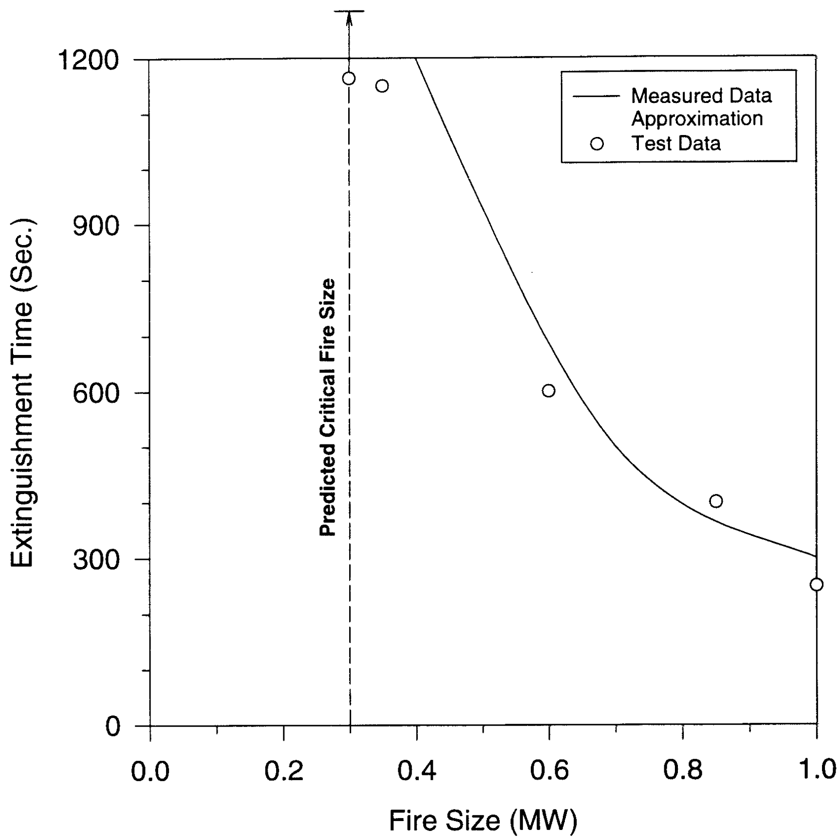


Figure 16. Critical fire size comparison

conditions, and the gas concentrations in the space. These measurements were taken during the local application evaluation. The previous phase of this investigation [3] provided information on the conditions in the compartment during extinguishment of a fire using a total flooding water mist system.

The evaluation focused on the fires conducted on the side of the mockup due to the inability of the mist system to extinguish these fires. For the fires that were extinguished, the conditions in the space were obviously dramatically improved.

Although the fires conducted on the side of the mockup were not extinguished, all of the mist systems were capable of dramatically reducing the thermal effects produced by the fires (Table 11). It was shown that during these tests, between thirty and seventy percent of the energy released by the fire was absorbed by the mist. This was apparent by a reduction in temperatures observed in the space. The radiation from the fire was also reduced by sixty to ninety percent. Based on the oxygen concentrations measured during these tests, the mist had little effect on reducing the size of these fires. Consequently, the mist had little effect on the gas concentrations in the space. The mist was also observed to have a limited impact on the visibility in the space. During the discharge of mist, the optical density low in the space remained constant while the optical density high in the space was slightly increased.

In summary, the water mist systems evaluated during these tests, were capable of extinguishing a majority of the test fires, allowing the conditions in the compartment to quickly return to ambient. In the cases where the fires were not extinguished, the thermal conditions in the space (radiation and temperatures) were significantly reduced, but the gas concentrations and visibility were relatively unaffected by the mist.

10.0 CONCLUSIONS

The information collected during this test series supports the following conclusions.

Local Application Evaluation

- Local application water mist systems are capable of extinguishing a variety of heptane or diesel spray and pool fires if the systems are designed properly and the mist reaches the fire (Complete coverage of the object being protected with a mist concentration greater than 50 g/m^3 and a mist velocity greater than 1.0 m/s).

- To ensure that the mist reaches the fire, these systems should be designed to produce complete spray pattern coverage of the object being protected (near uniform mist density with no holes in spray patterns).

- Local application water mist systems have limited ability against obstructed fires. Fires located behind even the smallest obstruction can be too challenging for current technologies.

- The local application water mist systems evaluated during this investigation were only capable of extinguishing a spray fire when the nozzles were located above the fire. Only one spray fire was extinguished using an horizontal attack (nozzles located on the side of the fire).

- Large spray fires are slightly easier to extinguish than smaller spray fires.

- When the fires are not extinguished, thirty to seventy percent of the energy released by the fire is absorbed by the mist. The radiation released by the fire was also reduced by sixty to ninety percent.

- The results of these tests identify many deficiencies in the draft test method and will be discussed in the following section of this report.

Fire Obstruction Evaluation

- Small obstructed heptane pan fires could not be extinguished with the total flooding water mist system included in this evaluation.

- Small obstructed diesel fuel pan fires were significantly easier to extinguish than heptane and were extinguished in a majority of these tests (independent of fire obstructions and pre-burn time).

- The size of the obstruction and the separation distance between the obstruction and the fire were identified as the primary variables associated with the effectiveness in the extinguishment of these fires. As the size of the obstruction is increased or the distance between the fire and the obstruction is decreased, the extinguishment times increase.

- Fires were easier extinguished when located higher in the space (closer to the mist nozzles and in areas of high mist velocity).

Scaling Evaluation

- The steady state model developed during the initial phase [3] of this investigation was validated for a range of fire sizes, ventilation conditions and water mist flow rates. The model was able to accurately predict the steady state compartment temperatures, oxygen concentrations and critical fire size for the tests conducted during this investigation. The model has served as the foundation for the development of a transient model.

- Compartment Environment Evaluation

    - A majority of the fires conducted during the local application evaluation were extinguished by the mist systems. For the fires that were not extinguished, the mist system was capable of dramatically reducing the thermal conditions in the compartment (temperature and radiation). The mist system had little effect on visibility and gas concentrations in the space.

11.0 CRITIQUE OF THE DRAFT TEST METHOD FOR WATER-BASED LOCAL FIRE-EXTINGUISHING SYSTEMS (FP40/5/9)

The draft test method for evaluating water-based local fire-extinguishing systems submitted to the IMO by Japan is found in Appendix A. The test method evaluates the extinguishment capabilities of a single water mist nozzle installed the maximum allowable distance away from the fire as identified in the manufacturers' installation specification. The nozzle is evaluated against pan and spray fires produced using either diesel or hexane as the fuel depending on the intended application (hexane for cargo pump rooms and diesel fuel for machinery spaces). The fires produce the following heat release rates: pan - 2.0 MW, spray - 4.0 MW. The fires are positioned directly under the nozzle (center of the spray pattern) and must be extinguished within fifteen minutes of mist system activation. The results of the tests conducted by the U.S. Coast Guard identify many of the deficiencies in this test method. These deficiencies are described in the following paragraphs.

The test method lacks the ability to evaluate the limits on the water mist nozzle(s) spacing. The tests should be conducted against an array of nozzles (preferably a three by three array) with the fires located both under one nozzle as well as between four nozzles.

The test method evaluates the capabilities of the system with the nozzles installed the maximum distance away from the hazard, but does not address the minimum. The minimum distance also needs to be evaluated/identified during the test.

Prior to the U.S. Coast Guard's investigation, there was limited data on the ability of local application water mist systems to extinguish spray fires. The U.S. Coast Guard's tests identified a variation in extinguishment capabilities as a function of spray fire size (larger fires were easier to extinguish (were extinguished more quickly than smaller spray fires)). The draft test method lacks the data to support the selection of the 4.0 MW spray fire included in the evaluation. Based on the U.S. Coast Guard's tests, a 1.0 MW spray fire is recommended to evaluate local application water mist systems.

The draft test method submitted by Japan to the IMO (FP40/5/9) requires that systems to be installed in Cargo Pump Rooms be evaluated using hexane as the test fuel. There is little, if any, data available on water mists ability to extinguish hexane fires. However, the results of Coast Guard tests along with the data collected during the development and acceptance testing of total compartment protection water mist systems [1] provide a substantial data base for n-heptane fires. Although we would expect similar results with hexane and heptane, it is recommended that n-heptane be used as the test fuel for Cargo Pump Rooms rather than hexane.

12.0 REFERENCES

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Appendices A-D are not included in this file. To obtain a copy of Appendices A-D, please contact Mr. Richard Hansen at 860-441-2866 or rhansen@rdc.uscg.mil.

APPENDIX A - IMO Test Protocol & Japanese Proposal

APPENDIX B - Water Mist Spray Nozzle Characteristics

APPENDIX C - Instrumentation and Camera Details

APPENDIX D - Test Data